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Laboratory-Determined Concentration Factors and Elimination Rates of Some Anthropogenic Radionuclides in Marine Vertebrates and Invertebrates

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Literature is reviewed and summarized with regard to concentration factor values and biological elimination rates determined in laboratory experiments for several anthropogenic radionuclides. Comparison is made with concentration factors measured *in situ* in the marine environment.

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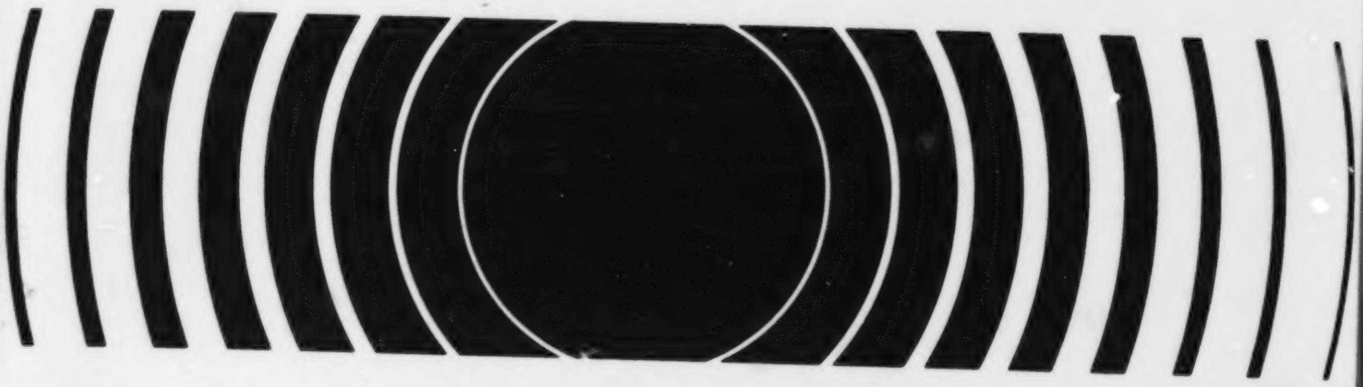

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U.S. Environmental Protection Agency
Washington, DC 20460

FOREWORD

In response to the mandate of Public Law 92-532, the Marine Protection, Research and Sanctuaries Act, as amended, the Environmental Protection Agency (EPA) has developed a program to promulgate regulations and criteria to control the ocean disposal of radioactive wastes. An important technical consideration in any environmental assessment of this option is the potential for biological uptake of radioactivity as it moves through marine food chains which could lead to man. An understanding of the range of concentrations and biological elimination rates of key radionuclides found in marine organisms is fundamental.

This report reviews and summarizes the experimental literature on radionuclide concentration factors and biological turnover rates of selected radionuclides. It also provides a comparison of laboratory-determined concentration factors with field-derived values. The isotopes of low-level waste selected for inclusion are plutonium, americium, cesium, strontium, and cobalt. The data are presented by isotope and according to the various groups of marine organisms for which data are available. The concentration factor data are summarized in tables that include comments concerning conditions of the experiment. Figures are included that compare laboratory and field-derived concentration factor values for each isotope.

These data are useful for predictive modelling both to estimate concentrations of specific nuclides which may occur in fish or invertebrates from any past or future ocean disposal activities and to predict the resultant dose to man from ingestion of these seafoods.

The Agency invites all readers of this report to send any comments or suggestions to Mr. David E. Janes, Director, Analysis and Support Division, Office of Radiation Programs (ANR-461), Environmental Protection Agency, Washington, D.C. 20460.

Sheldon Meyers

Sheldon Meyers, Acting Director
Office of Radiation Programs (ANR-458)

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LABORATORY-DETERMINED CONCENTRATION FACTORS AND ELIMINATION RATES OF SOME ANTHROPOGENIC RADIONUCLIDES IN MARINE VERTEBRATES AND INVERTEBRATES

ABSTRACT

The literature on radionuclide concentration factors and elimination rates acquired in laboratory experiments is reviewed and discussed, and then the laboratory-derived concentration factors are compared to those concentration factors measured directly in organisms collected from marine environments. The radionuclides considered in this review are those of plutonium, americium, cesium, strontium, and cobalt. The groups of organisms for which data have been acquired are primary producers, annelids, molluscs, arthropods, and fishes.

I discuss the measurement, application, and patterns of concentration factors, as well as the derivation and determination of elimination-rate constants. In addition, I have compiled tables of concentration factors and elimination rates for those radionuclides and groups of organisms for which sufficient data are available.

INTRODUCTION

OBJECTIVE

The objective of this study is to provide data that can be used to assess the potential for bioconcentration of radioactivity in marine food chains that could lead to man. Specifically, the literature on radionuclide concentration factors and elimination rates acquired in laboratory experiments is reviewed and discussed, and then the laboratory-derived concentration factors are compared to those concentration factors measured directly in organisms collected from marine environments. Radionuclides designated by the U.S. EPA Office of Radiation Programs for inclusion in this review are those of plutonium, americium, cesium, strontium, and cobalt. Tables of concentration factors and elimination rates for major groups of organisms were compiled for those radionuclides for which sufficient data were available.

CONCENTRATION FACTORS

Concentration factors have been used in models to predict the concentration of radionuclides when releases from ocean waste disposal or ocean discharges are continuous and steady-state conditions are present. The concentration factor (CF) is usually defined as the ratio of the concentration of the radionuclide (R) in the organism or tissue i, (R_i), to that in the water, (R_W). Thus, if the concentration of a radionuclide in the water in an ecosystem is known, the concentrations in aquatic organisms can be calculated from their CFs. Some authors have calculated CFs from the concentration of the radionuclide in the soluble fraction of the water; others have used total water concentrations. Furthermore, some CFs have been calculated from radionuclide concentrations in food-chain organisms and in sediments. The use of CFs based on specific biotic and abiotic components is appropriate when sufficient data are available that indicate that the component (or components) is the actual source of the radionuclide to the organism of concern.

CFs are affected both by the physical and chemical form of the element in the environment and by the route of entry of the element into the organism. Many physicochemical forms of radionuclides may exist, and the distribution among forms differs with the radionuclide and the characteristics of the ecosystem (Fig. 1). The routes of entry of radionuclides into an organism are dependent in part on the organism's feeding behavior and its habitat. Major routes of entry are from radionuclides in solution or suspension in water and in food-chain organisms. However, many organisms live in sediments and may absorb radionuclides from interstitial waters, from the sediment directly, and from ingestion of sediments. Unfortunately, for many radionuclides we do not know the relative bioavailability of the different physicochemical forms or the relative importance of the food, water, and sediment pathways for transfer of the radionuclides to the organisms.

Measurement of Concentration Factors

Let us consider some of the parameters affecting the measurement of concentration factors. Variations in concentration of stable and radioactive nuclides in organisms can be expected because of differences in their sizes, ages, and reproductive states and because of fluctuations in temperature and the concentration of constituents in the environment. If, as has been frequently done, field measurements of stable or radioactive nuclide concentrations of organisms are made at only one point in time and on only limited numbers of the population, the CFs obtained may be erroneous. Thus, to obtain a meaningful measurement of CF, we may need a knowledge of the environmental history of the organism and the composition (size, age, and sex) of the population sampled.

In addition to variations in concentration in the organisms, changes in concentration in the water occur because of seasonal fluctuations both in the run-off from the land and in the hydrodynamic and meteorologic conditions. Furthermore, more than values for just the total concentration of the nuclide in the water may be required. It may be necessary also to have the values for the concentrations of prominent chemical and physical species because an organism may possibly accumulate only one specific form. Consequently, for a CF to be valid, it should be established both that the concentration measured in the water is that with which the organism has equilibrated and that it is for the physicochemical form that existed during the period of equilibration.

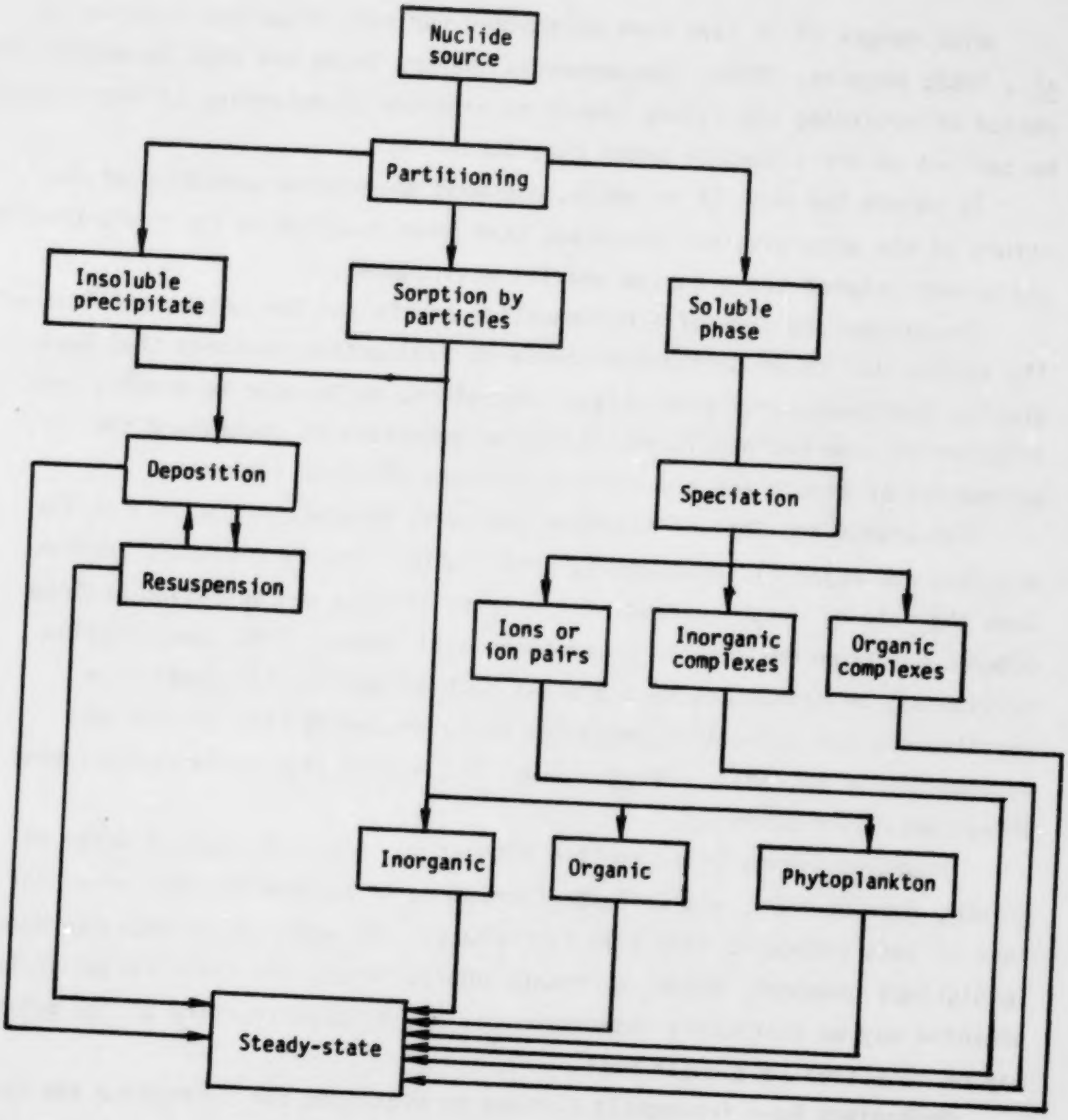
Nuclide source
Partitioning
Insoluble precipitate
Sorption by particles
Soluble phase
Deposition
Resuspension
Speciation
Ions or ion pairs
Inorganic complexes
Organic complexes
Inorganic
Organic
Phytoplankton
Steady-state

Figure 1. Hypothetical model of the partitioning of a radionuclide among compartments in aquatic ecosystems.

Application of Concentration Factors

Wide ranges in CF have been determined for some organisms (Jackson *et al*., 1983; Noshkin, 1985). Consequently, before these are used in models, the method of obtaining the values should be examined to determine if they should be applied to the situation under consideration.

To select the best CF to apply, one must understand something of the nature of the physiological processes that have resulted in the concentration difference between the organism and its environment.

The uptake and loss of a radionuclide may follow the uptake and loss of its stable nuclide or of related stable or radioactive nuclides that have similar physicochemical properties. Therefore, to be able to predict the behavior of some radionuclides, it may be necessary to understand the metabolism of stable and radioactive nuclides of other elements.

The uptake and loss of elements continues throughout the life of the organism and may vary considerably with fluctuations in metabolic demands. When the rate of uptake exceeds the rate of loss, a concentration buildup between the organism and its environment will ensue. This concentration buildup may be maintained by a process such as binding to subcellular constituents and cellular metabolites or by processes that require the expenditure of metabolic energy. Thus, CFs may be altered by factors that affect metabolic activity.

The accumulation of a specific element may occur because of needs of growth, reproduction, and skeleton formation, or because the mechanism for loss is less effective than that for uptake. The material accumulated may be in distinct chemical, organ, or tissue pools. Thus, its distribution in the organism may be distinctly heterogeneous, and a large fraction of the material may be localized in a small mass.

Mechanisms have frequently evolved in organisms for increasing the rate of uptake of an element when the environmental concentrations are low and decreasing it when metabolic demands have been met. When an excess of an element is accumulated, there is a need for its removal. Excesses can be lost by elimination of the element back across the body surface or gills and excreting it into the gut or the urine, or can be metabolically inactivated by temporarily or permanently storing it in a different form in a particular tissue. Tissues known to be important storage sites for many elements are the liver (or hepatopancreas) and the kidney. Some aquatic organisms appear to be able to regulate the concentration of elements by combining the processes of absorption, excretion, and storage. The ability of organisms to regulate element concentrations has been assessed by analyzing tissues from organisms exposed to different concentrations of the element of interest. Homeostatic control of element concentrations has been demonstrated for a number of elements in fishes, but for only a few elements in invertebrates.

Accumulation can be affected also by the modifications that may occur at the place of uptake because of the specificity of the binding sites. Furthermore, because these sites may not discriminate between elements that are chemically and physically similar, inhibition of uptake may occur as a consequence of competition for binding sites. Absorption of elements from seawater may occur across the general body surface or through a special area such as gills or walls of the gut (Fig. 2). Once in the body fluid, they may remain free or bind to proteins, or they may be accumulated by individual tissues. This appears to involve sorption at sites on or within the cells. Absorption may be an active or passive process, and accumulation may be related to the stabilities of complexes formed between elements and organic ligands.

Patterns of Concentration Factors

Three idealized CF patterns have been described by Vanderploeg et al. (1975). The first pattern is that the CF for a radionuclide (R) in organism or tissue i, $CF(R)_i$, is constant, i.e., is unaffected by the concentration of elements:

$$CF(R)_i = \text{constant}. \tag{1}$$

This pattern is shown by radionuclides that are not under homeostatic control and is exemplified by the behavior of plutonium in marine invertebrates and fishes.

The second pattern is seen in organisms in which the concentration of an element in an organism or tissue is under homeostatic control or regulated at a constant concentration despite different concentrations of the element in water. In this case, the CF of the element (E) is inversely proportional to its concentration in the water:

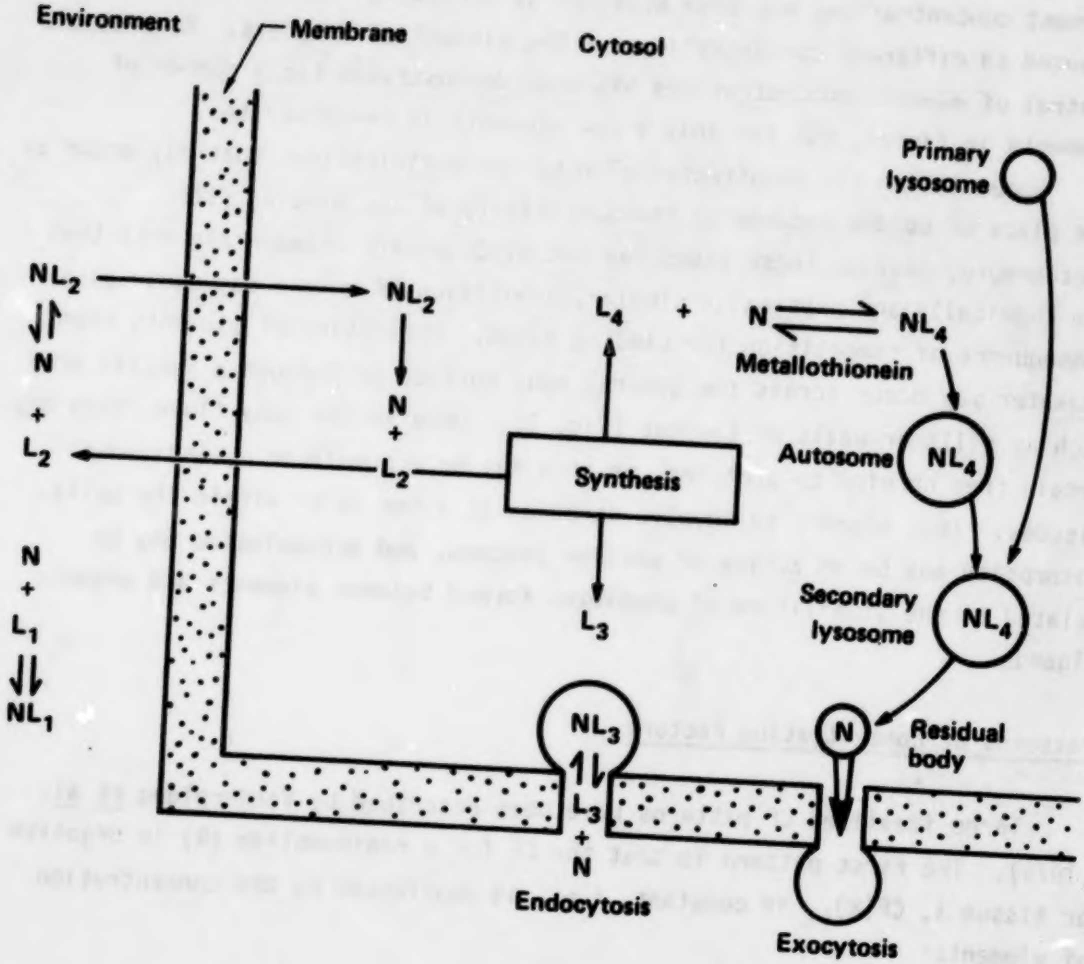
Environment
Membrane
Cytosol
NL_2
N
NL_2
N
+
L_2
L_2
Synthesis
L_4
+
N
NL_4
Metallothionein
Primary lysosome
Autosome
NL_4
Secondary lysosome
NL_4
L_3
N
+
L_1
NL_1
NL_3
L_3
+
N
Endocytosis
N
Residual body
Exocytosis

Figure 2. Processes in uptake, incorporation, and loss of stable and radioactive nuclides of metals (modified from George and Viarengo, 1985). Nuclide (N) in seawater and/or in the cytosol may be associated with ligands (L) of different molecular size and affinity for the metal. Within the cytosol, nuclides bound to ligands may be associated with metallothioneins and lysosomes.

$$CF(E)_i = E_i/E_w \, , \tag{2}$$

where E_i = concentration of stable element in organism or tissue i, a constant (μg/g wet weight), and

E_w = concentration of stable element in water (μg/g).

If it is assumed that the specific activity (i.e., the ratio of radionuclide concentration to the stable element concentration) in i is equal to that of the water, the CF for the radionuclide, $CF(R)_i$, is also inversely proportional to the concentration of the stable element:

$$CF(R)_i = E_i/E_w \, . \tag{3}$$

This pattern is exemplified by radionuclides of some elements in fishes, but by few elements in invertebrates. The classical example of this pattern is the behavior of I^{131} in mammals in which the concentration of iodine is under strict control.

The third pattern is that the CF for the radionuclide, $CF(R)_i$, is inversely proportional to the concentration of a nonisotopic carrier element in water (i.e., chemically similar to but occurring in higher concentrations than the stable-element analogue). The derivation of this relationship follows.

The CF for radionuclide R is related to $CF(E^*)_i$, the CF for the carrier element E^*, by

$$CF(R)_i = CF(E^*)_i \, \frac{CF(R)_i}{CF(E^*)_i} \, , \tag{4}$$

which may be written as

$$CF(R)_i = CF(E^*)_i \, \frac{(R/E^*)_i}{(R/E^*)_w} \, , \tag{5}$$

where $(R/E^*)_i$ and $(R/E^*)_w$ are ratios of radionuclide concentration to carrier-element concentration found in the organism or tissue and in the water, respectively. Assume that the nonisotopic carrier element is homeostatically controlled in the organism, that is:

$$CF(E^*)_i = E_i^*/E_w^* \, , \tag{6}$$

where E_i^* = concentration of nonisotopic carrier element in organism or tissue i, a constant (µg/g wet weight),

and E_w^* = concentration of nonisotopic carrier element in water (µg/g).

Combining equations (5) and (6) and letting $q_i = (R/E^*)_i/(R/E^*)_w$, the desired expression is obtained:

$$CF(R)_i = \frac{q_i E_i^*}{E_w^*} \, . \tag{7}$$

This pattern is shown by very few radionuclides in marine organisms. The classical example of this pattern is the behavior of radionuclides of cesium in fresh-water animals; the nonisotopic carrier element is potassium in this case.

ELIMINATION RATES

The accumulation of the stable or radioactive nuclide of an element by any pathway can involve a number of different processes. If the rate-determining process can be described mathematically, a model can be developed to predict changes in concentration with time and location. A considerable effort has been made to develop models to predict the distribution of radionuclides released into the environment. The types of models developed to predict concentrations of radionuclides in aquatic organisms include equilibrium and dynamic models.

The type of model to be used in a given situation depends on the nature of the release and on the properties of the ecosystem. When releases of radionuclides are continuous and steady-state conditions are present, an equilibrium model such as a CF model can be used. In this case, the important parameter needed for the model is the CF, and the concentration in the animal is determined by multiplying the concentration in the water by the CF. In the case of accidental episodic releases, the result is a dynamic situation in which organisms accumulate the material for a relatively short period and then lose it with a characteristic rate constant. In this case, the important parameters needed for the model are CFs and biological elimination-rate constants.

The elimination rate of stable and radioactive nuclides in organisms depends on dynamic processes of exchange with elements in the environment. Compartments of elements are identified from a mathematical analysis of the changes in concentration during accumulation or loss. The resolution of compartments is limited by experimental error, and the compartments that can be identified are those whose concentrations differ significantly in their elimination-rate constants. These compartments may be physiological, structural, or chemical entities, and their metabolic significance may not be known.

The biological half-life of a radionuclide in an organism depends upon the organism and the properties of any element to which it may be related. Data available on biological half-life of radionuclides indicate that, in most marine organisms, the transfer of radionuclides to and from the water can be described by one- or two-compartment models. In small organisms with a large surface-to-volume ratio, the biological half-life of monovalent elements such as sodium or cesium may be minutes, whereas in large organisms and multivalent elements, it may be months. The biological half-life is also a function of the metabolism of the element by the organism. The quantities accumulated by organisms when the concentrations are increased in the water differ greatly for those elements that are and those that are not under homeostatic control.

Derivation of Elimination Rates

The rate of change in concentration of a radionuclide (corrected for radioactive decay to time zero) in an organism at any time may be described by:

$$dR_i(t)/dt = k_1 R_w(t) - k_2 R_i(t) , \tag{8}$$

where

$R_w(t)$ = the concentration in the water at time t,
$R_i(t)$ = the concentration in the organism or tissue i, at time t,
k_1 = the biological accumulation-rate constant,
k_2 = the biological loss-rate constant.

At steady-state conditions, $R_w(t)$ = constant and $dR_i(t)/dt = 0$, and

$$k_1R_w = k_2R_i(s), \text{ and } CF = \frac{R_i(s)}{R_w} = \frac{k_1}{k_2}, \qquad (9)$$

where

$R_i(s)$ = the concentration in the organism or tissue i, at steady-state conditions.

If it is assumed that the radionuclide concentration in the water at any time t is a constant, then equation 8 upon integration becomes:

$$R_i(t) = \frac{k_1R_w}{k_2}[1 - e^{-k_2t}] \ . \qquad (10)$$

Substituting $R_i(s) = k_1R_w/k_2$ into equation 10, we have:

$$R_i(t) = R_i(s)\ [1 - e^{-k_2t}] \ . \qquad (11)$$

In those situations where the concentration in the organism is not at steady-state conditions and the concentration in the water is known and is constant, the ratio of the concentration in the animal to that in the water (CF^*) can be substituted for concentrations in the animal to give:

$$CF^*(t) = CF(s)\ [1 - e^{-k_2t}] \ , \qquad (12)$$

where

$CF^*(t)$ = the nonsteady-state concentration factor in the organism at time t,

$CF(s)$ = the concentration factor in the organism at steady-state conditions.

The loss of stable or radioactive (corrected for radioactive decay to time zero) nuclides may be described by:

$$R_i(t) = R_i(o)\ [e^{-k_2t}] \ , \qquad (13)$$

where

$R_i(o)$ = the radionuclide concentration in the organism at time zero, the time of equilibrium or cessation of exposure.

From k_2, the biological half-life (T 1/2) of a nuclide in an organism may be determined from the relationship:

$$T\,1/2 = \frac{0.693}{k_2} \quad . \tag{14}$$

Determination of Elimination Rate Constants

The kinetics of radionuclide metabolism have been assessed both in whole organisms and in specific body parts. Some of the techniques used to determine elimination rates are by monitoring:

- the rate of uptake of radionuclides in organisms exposed to radionuclides under controlled laboratory conditions,
- the rate of uptake of radionuclides in organisms transferred from a pristine to a radionuclide-contaminated environment,
- the rate of loss of radionuclides in organisms exposed to radionuclides under controlled laboratory conditions and then transferred to a pristine environment, and
- the rate of loss of radionuclides in organisms transferred from a radionuclide-contaminated environment to a pristine environment.

The extrapolation of the kinds of data derived from these types of experiments to specific field conditions must be done with care. For example, it is extremely difficult to design laboratory experiments that simulate real-world conditions and provide the kinds of information required to predict the accumulation and redistribution by marine organisms of radionuclides released into ecosystems. Ideally the radionuclide should be presented to the test organisms in a manner similar to that which would occur in its habitat. In the environment, the radionuclide may be present in the particulate and soluble fraction of the water in different physicochemical forms, has been incorporated into the food chain, and has been deposited in the sediments. Most laboratory experiments performed do not have all abiotic compartments represented, and the physicochemical form of the radionuclide to which the organisms are exposed is not defined. Also, the test organisms should be fed, and the population densities in the experimental container should be representative of those found in the natural habitat. For many organisms, insufficient data are available on their ecology to permit realistic experimental design. Furthermore, most laboratory experiments are not conducted long enough to permit steady-state conditions of uptake and loss to be achieved in all compartments; this results in underestimation of CF values. In spite of these limitations, data have been acquired on elimination rates and accumulation factors that can be used to evaluate the dynamics of radionuclide transfer in marine food chains.

PLUTONIUM

PHYSICOCHEMICAL FORM

The chemistry of plutonium is complex and is partly governed by the total concentration in solution. Multiple oxidation states can coexist in solution and the oxidation-reduction behavior is complicated (see review of Watters et al., 1980). There are four principal sources of data on the behavior of plutonium: world-wide fallout; nuclear test sites (Marshall Islands and Nevada); Thule, Greenland; and nuclear power plant outfalls.

The behavior of plutonium in seawater has been studied in widely different ecosystems, and the concentrations measured differ by as much as three orders of magnitude. Because the pH of the ocean is well buffered, plutonium apparently cannot exist except as Pu(III) or Pu(IV) in solution in the water column (Watters et al., 1980). Plutonium has a high affinity for particulate material. This is described by a distribution coefficient (K_d):

$$K_d = \frac{fs}{(1 - fs)} \, \frac{V}{W} ,$$

where

fs = fraction of nuclide on the particulate fraction

$1 - fs$ = fraction of nuclide in the soluble fraction

V = weight of water (g)

W = dry weight of particles (g).

The K_d as defined is dimensionless, and greater sorption of the nuclide to the particulate fraction results in higher K_ds.

The mean K_d recommended for use in models of both the pelagic and coastal regions of the ocean is 100,000; the range of values recommended for sensitivity analysis is from 10,000 to 1,000,000 (International Atomic Energy Agency (IAEA), 1985). The oxidation state of plutonium on particles is considered to be Pu(IV). Somewhere in the concentration range of 10^{-13} to

10^{-6} M, plutonium ceases to exhibit the properties of simple ions, and the possible formation of polymeric species must be considered (Watters et al., 1980). Consequently, when moderately concentrated solutions are used in laboratory experiments, the results should not be used to predict the behavior of plutonium in the environment.

PRIMARY PRODUCERS

Concentration Factors

Microalgae. Studies have shown that plutonium can be strongly concentrated by primary producers (Jackson et al., 1983). However, few experimental studies of plutonium uptake by marine phytoplankton have been conducted despite their importance in geochemical cycling and food chain processes (Table 1 and Fig. 3). Fisher et al. (1980) used environmentally realistic atom concentrations to test the plutonium uptake by Thalassiosira pseudonana, Thalassiosira sp., Platymonas sp., and glass particles. Yen (1981) described the sorption of plutonium by two species of marine phytoplankton. More recently, Fisher et al. (1983a) determined the ability of six clones of marine phytoplankton to accumulate plutonium.

CFs obtained by Yen (1981) and Fisher et al. (1983a) for phytoplankton tested in the laboratory demonstrated about an order of magnitude difference with species (Table 1). Some values obtained in the field were lower than those obtained under laboratory conditions (Fig. 3). It is not known whether the low values were due to differences in species or to the absence of steady-state conditions. The former is probably the reason because steady-state conditions are reached relatively rapidly in phytoplankton (Fisher et al., 1983a). Also, it would be expected that CF values determined in the laboratory would be similar to those determined in the field if the organisms were exposed to the same physicochemical forms of plutonium.

Dissolved organic matter (DOM) was found to affect the accumulation of ^{237}Pu (III-IV) and ^{237}Pu (V-VI) by the marine diatom Thalassiosira pseudonana (Fisher et al., 1983b). Ethylenediaminetetraacetate at 0.3 μM reduced plutonium uptake, but marine fulvic and humic acids, naturally occurring DOM, and diatom exudates did not reduce uptake.

Table 1. Laboratory-derived concentration factors (CFs) for plutonium in primary producers.

Organism	Exposure, d	CFs	Comments
		Microalgae	
Thalassiosira pseudonana[a]	1	85,000-2,800,000	Varied with biotic and abiotic factors
T. pseudonana[b]	4	380,000	3H clone
Dunaliella tertiolecta[b]	4	150,000	Dun clone
Oscillatoria woronichinii[b]	4	50,000	OSE N4 clone
Emiliania huxleyi[b]	4	50,000	MCH No.1 clone
E. huxleyi[b]	4	330,000	BT-6 clone
Tetraselmis chuii[b]	4	60,000	Tet C2 clone
Monochrysis lutheri[c]	1	8100 ± 5600	At 24°C
M. lutheri[c]	1	24,300 ± 3700	At 0°C
M. lutheri[c]	1	32,800 ± 10,700	At 24°C
M. lutheri[c]	1	34,200 ± 15,900	At 24°C
M. lutheri[c]	1	44,900 ± 12,500	At 24°C
Phaeodactylum tricornutum[c]	1	38,100 ± 19,800	At 24°C
P. tricornutum[c]	1	46,500 ± 10,700	At 0°C
P. tricornutum[c]	1	72,300 ± 26,600	At 24°C
		Macroalgae	
Ascophyllum nodosum[d] (brown algae)	15	797	--
A. nodosum[d]	15	415	--
A. nodosum[d]	15	298	--
A. nodosum[d]	15	578	--
A. nodosum[d]	15	738	--

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[a] Fisher et al. (1980).

[b] Fisher et al. (1983a).

[c] Yen (1981).

[d] Zlobin and Mokanu (1970).

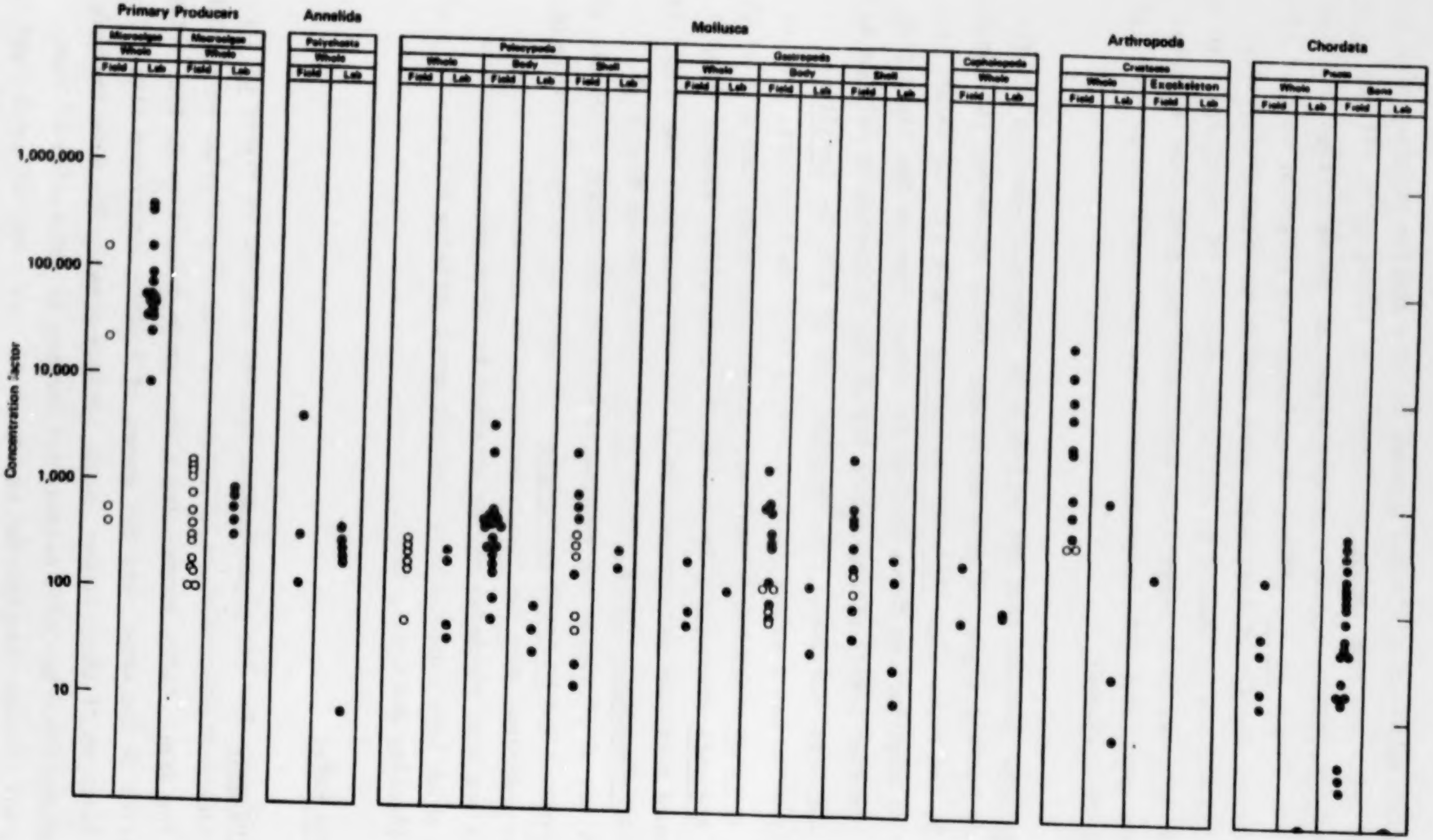

Figure 3. Concentration factors (CFs) for plutonium in marine biota: laboratory-derived CFs from this report (●); field-derived CFs from Noshkin (1985) (●) or Jackson et al. (1983) (o).

The accumulation of plutonium appears to be a passive process; dead cells accumulated about the same amount of plutonium as living cells (Fisher et al., 1980). Also, quantities accumulated were higher at low salinities and high temperatures. Fisher et al. (1983a) investigated the effect of valence state on accumulation; the CFs of Pu(III-IV) were similar to those of Pu(V-VI). However, Pu(V-VI) may be reduced to Pu(III-IV) once it is associated with the cells. The data available support the hypothesis that plutonium in marine environments associates with suspended particles that could act as vertical vectors for this element.

Macroalgae. Limited data are available on laboratory-derived CFs for plutonium in benthic algae. Zlobin and Mokanu (1970) determined the uptake of plutonium by the brown algae *Ascophyllum nodosum* (Table 1). CF values were the same order of magnitude as those derived for other algae in the field (Fig. 3). Guary and Fraizier (1977) proposed that the CF for plutonium is related to the nature of the algal surface. They reported a CF of 1175 for *Corallina officinalis* which has a calcified and strongly ramified structure, a CF of 523 for *Fucus serratus* which has a ramified, noncalcified blade, and a CF of 85 for *Laminaria digitata* which has a large, smooth, noncalcified blade. Wong et al. (1972) showed plutonium was accumulated on the very outermost (mucilage) layer of the kelp *Pelagophycus porra*. Spies et al. (1981) showed that high concentrations of plutonium are associated with the coenocytic filaments in the calcareous algae *Halimeda macrophysa*. Evidence currently available on macroalgae indicates that the likely mechanism for accumulation is by adsorption and that plutonium may be attached to large macromolecules or micelles, which have slow diffusivities but great affinity for a variety of surfaces (Beasley and Cross, 1980).

Elimination Rates

Microalgae. For the phytoplankton species examined by Fisher et al. (1983a), steady-state conditions of uptake and loss of plutonium were reached within a few days. Cells accumulated plutonium in proportion to the isotope concentration in the water, and the amount of isotope associated with cells was a direct function of their number (hence surface area). The data indicate that isotope accumulation by cells ceased, not because of saturation of their surfaces, but because they reached steady-state conditions of uptake and loss from the surfaces. Uptake was strongly affected by the nature of particle surfaces, and cells from rapidly growing cultures took up more plutonium than did those that were in late log phase of growth or were senescent (Fisher et al., 1980). Such differences prevailed even in experiments during which little or no cell division took place. The authors state that most of the differences in cellular plutonium levels in their experiments can probably be attributed to differences in surface physiology related to the growth stages of the cultures used for inocula. Cells accumulated more plutonium from UV-treated seawater than from untreated or enriched seawater.

Macroalgae. Accumulation of plutonium in the brown algae Macrocystis pyrifera appeared to be relatively rapid; steady-state conditions of uptake and loss were reached within a few days (Hodge et al., 1974). Spies et al. (1981) measured the rate of loss of plutonium from Halimeda incrassata that had been transferred from a highly contaminated crater in the Enewetak Atoll to the lagoon that had a relatively low level of plutonium. The loss of plutonium was found to be biphasic. Most of the plutonium was in a fast-exchanging compartment that had a half-life of 1.4 d; the slow-exchanging compartment had a half-life of about 30 d.

ANNELIDA - POLYCHAETA

Concentration Factors

Accumulation of plutonium by polychaete worms is of interest because they live in the sediments and belong to a zoological group that occurs in deep water. These organisms are expected and have been found in oceanic radioactive waste disposal sites. Also, Noshkin et al. (1971) found that Nereis sp. contained the highest plutonium concentrations of all invertebrates that they analyzed. Fowler et al. (1975) showed that Nereis diversicolor readily accumulated ^{237}Pu (VI to IV) from seawater reaching CFs of about 200 (Table 2). The concentration of plutonium in the bioassay container was held relatively constant by changing the water daily and periodically adding some tracer to the water. A marked reduction of ^{237}Pu (VI) uptake was noted in worms accumulating the isotope from water that had been used for the first worm experiment. The authors suggest that ^{237}Pu might have become associated with excreted metabolites, e.g., mucus, and was thus rendered less available for bioaccumulation.

Table 2. Laboratory-derived concentration factors (CFs) for plutonium in Annelida - Polychaeta.

Organism	Exposure, d	CF_s	Comments
Hermione hystrix[a]	22	370 ± 10	Pu(III+IV), water
H. hystrix[a]	22	275 ± 11	Pu(V+VI), water
H. hystrix[a]	20	0.05 ± 0.01	Pu(III+IV) and (V+VI), sediments
Nereis diversicolor[b]	15	200	Pu(IV), water
H. hystrix[c]	27	130	Pu(IV), water
Arenicola marina[d]	21	7	Pu(VI), water
A. marina[d]	14	0.002	Pu(VI), sediment
Nereis diversicolor[e]	25	190	Pu, water
N. diversicolor[e]	25	0.001	Pu, sediment

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[a] Aston and Fowler (1984).

[b] Fowler *et al.* (1975).

[c] Grillo *et al.* (1981).

[d] Miramand *et al.* (1982).

[e] Murray and Renfro (1976).

A comparison was made of the uptake of ^{239}Pu from sediment and seawater by Nereis diversicolor (Murray and Renfro, 1976). Plutonium was added to the water and the sediment in the IV oxidation state; concentrations used in the experiments were between 10^5 and 10^6 times higher than those normally found under field conditions. Concentrations of ^{239}Pu in the worm increased throughout the 25-d exposure period, but steady-state conditions were not reached. The CF from the sediments was calculated to be 0.001, that from the seawater to be 190. Under the conditions of the experiment, it appears that N. diversicolor obtained most of its plutonium from the seawater. The authors compared the sediment CFs to those reported by Noshkin (1972) for a marine worm from Cape Cod; the value for day 15 was about two orders of magnitude less than those Noshkin (1972) measured in the environment.

The accumulation of sediment-bound $^{238-239}$Pu (VI) and of plutonium in seawater by the polychaete worm Arenicola marina was determined by Miramand et al. (1982). Bioavailability from the sediment was low; after 14 days of accumulation, the CF was only 0.002. Worms exposed to labeled seawater for 20 d had a CF of about 7.

The range of plutonium CFs in Annelida determined in the laboratory was lower than that determined in the field (Fig. 3). This is not unexpected because most of the exposure times were less than the biological half-life of plutonium observed in N. diversicolor (see below) and that might be expected in other polychaete worms.

Elimination Rates

The loss of plutonium was followed in N. diversicolor that accumulated ^{237}Pu (VI) for 8 d and then were transferred to nonradioactive water (Fowler et al., 1975). The half-life computed for between days 4 and 35 of the loss period was 79 d. Elimination of plutonium was followed also in Hermione hystrix that had accumulated ^{237}Pu from contaminated seawater (Aston and Fowler, 1984). The loss from the worms indicated the presence of two (at least) pools that had substantially different biological half-lives. The long-lived pool had a half-life of 54 d and the short one of 1.3 d.

MOLLUSCA

Concentration Factors

Pelecypoda. Bivalve molluscs have been used as indicator organisms of both stable and radioactive nuclides because of their particular efficiency in accumulating material from the water column. Because of this characteristic and its world-wide distribution, the mussel Mytilus edulis has been used as a sentinel organism (Goldberg et al., 1978). However, proper interpretation of trends in radionuclide concentrations require knowledge of the rates of elimination of the isotopes as well as their CFs.

Plutonium CFs determined in the laboratory are available for four different bivalve molluscs (Table 3 and Fig. 4). CFs varied with species and body part. The highest concentrations of plutonium were found in byssus threads (Fowler et al., 1975). High concentrations of other radionuclides have also been found in this material, but the mechanism of binding is not known. Higher CFs were found in the shell than in the body; the shell also contained the largest fraction of the activity. The high concentrations in the shell may primarily be the result of uptake by attached periphyton rather than of actual accumulation into calcified tissues.

Examination of the changes of plutonium concentration in the body with time indicated that none of these test organisms had reached steady-state conditions of uptake and loss with the plutonium in the media. This lack of equilibrium is the probable explanation for the range of the laboratory-derived CFs being lower than that of CFs derived in the field (Fig. 3).

Gastropoda. CFs for plutonium that were determined under laboratory conditions are available for only the gastropod Aporrhais pespelicani. Grillo et al. (1981) determined the accumulation, tissue distribution, and loss of plutonium in animals that were exposed to the isotope in the water for 20 d. Accumulation did not reach steady-state conditions in all tissues, and the CF values differed with the tissue and individual animals (Table 3). At the end of the uptake period, more than 80% of the activity was in the shell; the remaining activity was distributed about equally between the muscle and the viscera.

Table 3. Laboratory-derived concentration factors for plutonium in Mollusca.

Organism	Body part	Exposure, d	CFs	Comments
		Pelecypoda		
Venerupis decussata[a]	Whole	22	74 ± 5	Pu (III+IV), water, nonequilibrium
V. decussata[a]	Whole	22	61 ± 1	Pu (V+VI), water, nonequilibrium
V. decussata[a]	Whole	20	0.006	Pu(III+IV) and (V+VI), sediment
Mytilus galloprovincialis[b] (mussel)	Byssus	15-25	1900-4100	Varied with size and time
M. galloprovincialis[b]	Body	25	27-70	Varied with animal
Tapes decussatus (clam)[c]	Whole	17	140	Pu(IV), water
T. decussatus[c]	Shell	17	250	Pu(IV), water
T. decussatus[c]	Muscle	17	0-10	Pu(IV), water
T. decussatus[c]	Viscera	17	10-30	Pu(IV), water
Scrobicularia plana[d] (clam)	Whole	14	100	Pu(VI), sediment
S. plana[d]	Shell	14	0.01	Pu(VI), sediment
S. plana[d]	Body	14	0.005	Pu(VI), sediment
S. plana[d]	Whole	42	190	Pu(VI), water
S. plana[d]	Shell	42	360	Pu(VI), water
S. plana[d]	Body	42	40	Pu(VI), water
		Gastropoda		
Aporrhais pespelicani[c] (snail)	Whole	21	110	Pu(IV), water
A. pespelicani[c]	Shell	21	140-230	Pu(IV), water
A. pespelicani[c]	Body	21	20-130	Pu(IV), water
A. pespelicani[c]	Shell	21	10-20	Pu(IV), water
A. pespelicani[c]	Viscera	21	20-210	Pu(IV), water

Table 3. (Continued).

Organism	Body part	Exposure, d	CFs	Comments
	Cephalopoda			
Octopus _vulgaris_[e] (octopus)	Whole	15	65	Pu(IV), water
_O._ _vulgaris_[f]	Whole	15	65	Pu(IV), water
_O._ _vulgaris_[f]	Muscle	15	15	Pu(IV), water
_O._ _vulgaris_[f]	Hepatopancreas	15	50	Pu(IV), water
_O._ _vulgaris_[f]	Branchial heart and appendages	15	9300	Pu(IV), water

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[a] Aston and Fowler (1984).

[b] Fowler _et_ _al_. (1975).

[c] Grillo _et_ _al_. (1981).

[d] Miramand _et_ _al_. (1982).

[e] Guary _et_ _al_. (1981).

[f] Guary and Fowler (1982).

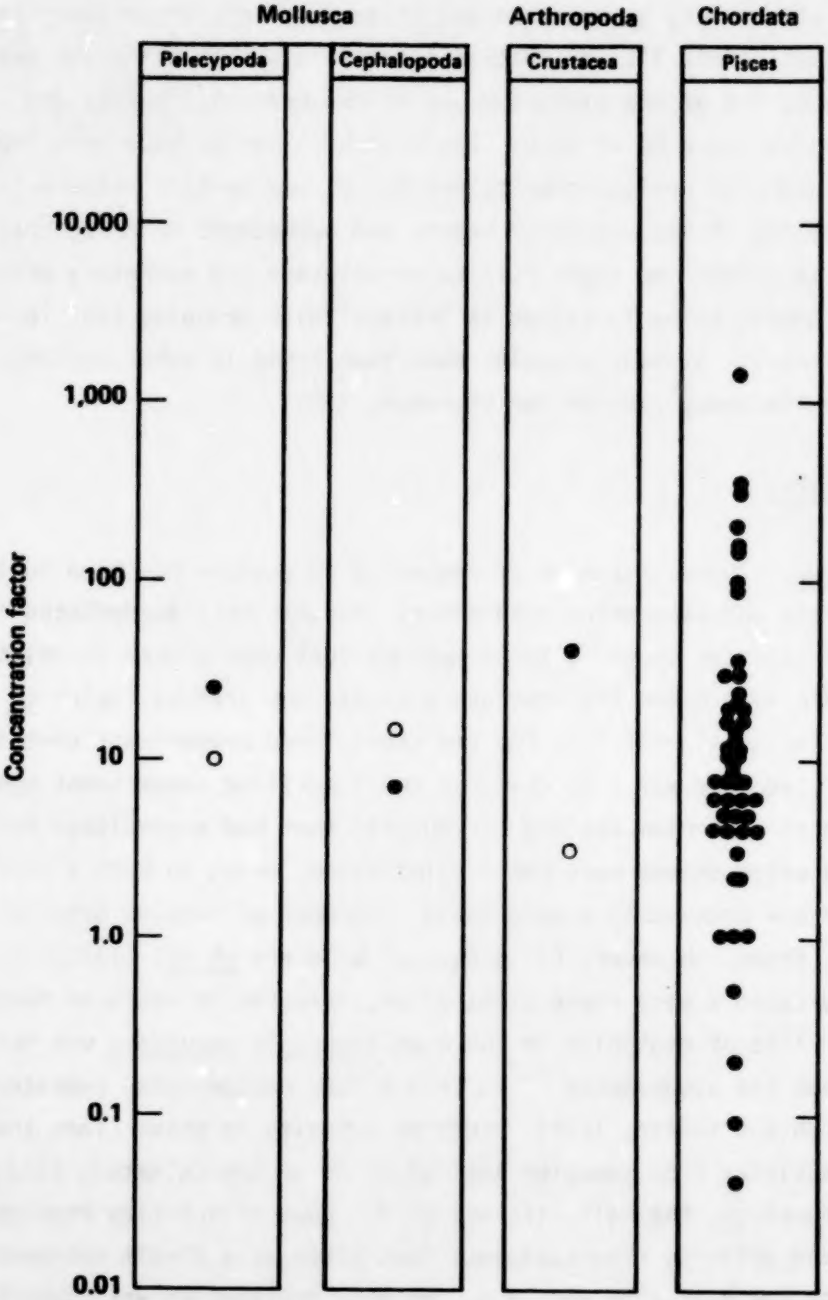

Figure 4. Concentration factors (CFs) for plutonium in muscle tissue of marine biota: laboratory-derived CFs from this report (o); field-derived CFs from Noshkin (1985) (●).

Cephalopoda. Data on accumulation of plutonium are available for Octopus vulgaris (Guary et al., 1981; Guary and Fowler, 1982). It is noteworthy that this octopus effectively accumulated and distributed plutonium among the internal tissues (Table 3). Of special interest was that after the two-week exposure period, 41% of the plutonium was in the branchial hearts and appendages, which had a CF of 9300. The branchial hearts have been implicated also in the uptake of cesium, cobalt, americium, and certain heavy metals. The unique ability of the branchial hearts and appendages to concentrate many elements may be related to their role in circulatory and excretory processes. The elements appear to be localized in intracellular granules that include pigmented material. Similar granules have been found in other molluscs and may be related to lysosomes (George and Viarengo, 1985).

Elimination Rates

Pelecypoda. The elimination of plutonium in mussels has been followed both under field and laboratory conditions. Mussels that accumulated Pu(IV) directly from seawater showed a two-component loss when placed in unlabeled seawater (Table 4). Under the laboratory conditions used by Fowler et al. (1975), the biological half-life for the short-lived compartment containing 35% of the total plutonium was 7 d; that for the long-lived compartment containing 65% of the total plutonium was 776 d. Mussels that had accumulated Pu(IV) from both food and water showed more rapid elimination, owing to both a shorter labeling time and presumably a more rapid clearance of labeled material eliminated as feces. However, field data of Goldberg et al. (1978) on ^{239,240}Pu indicated a very rapid elimination, measured in weeks or months.

The half-life of plutonium in the clam Venerupis decussata was followed in animals that had accumulated ^{237}Pu from either contaminated seawater or sediment (Aston and Fowler, 1984). Loss of activity in those clams that had accumulated activity from seawater took place as an approximately single exponential function; the half-life was 50 d. Loss of activity from those that had accumulated activity from sediments took place as a single exponential function also; the half-life was 24 d. No good explanation was given for the differences in loss rates. Because loss was followed only for 46 d in the seawater-contaminated clams and for 25 d in those contaminated from sediment, the presence of longer components could have been missed.

Table 4. Biological half-life (days) of plutonium in Mollusca.[a]

Organism	Body part	Pool A	Pool B	Pool C	Comments
		Pelecypoda			
Venerupis decussata[b] (clam)	Whole	50(100)	--	--	Pu (III+IV) and (V+VI), water
V. decussata[b]	Whole	24(100)	--	--	Pu (III+IV) and (V+VI), sediment
Mytilus galloprovincialis[c] (mussel)	Whole	776(65)	7(35)	--	Pu (VI), water
M. galloprovincialis[c]	Whole	39(100)	--	--	Pu (VI), water, labeled food
Tapes decussatus[d] (clam)	Whole	62(65)	7(35)	--	Pu(IV), water
M. galloprovincialis[e] (mussel)	Whole	193(30)	10(40)	2(30)	Pu(IV), water
M. galloprovincialis[e]	Whole	192(30)	13(40)	1(30)	Pu(VI), water
M. galloprovincialis[e]	Shell	215(30)	4(40)	--	Water
		Cephalopoda			
Octopus vulgaris[f] (octopus)	Whole	560(46)	2(30)	--	Pu(III+IV), water

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[a] Number in parentheses is the percent of total activity in the pool.

[b] Aston and Fowler (1984).

[c] Fowler *et al*. (1975).

[d] Grillo *et al*. (1981).

[e] Guary and Fowler (1981).

[f] Guary and Fowler (1982).

Gastropoda. The gastropod Aporrhais pespelicani lost ^{237}Pu at rates comparable to those of the clam Tapes decussata (half-life = 53 to 80 d) (Grillo et al., 1981).

Cephalopoda. The loss of ^{237}Pu from whole Octopus vulgaris was slow and appeared to take place from two compartments (Table 4). After a 70-d loss period, the majority (>90%) of the plutonium was in the branchial hearts and appendages (Guary and Fowler, 1982).

ARTHROPODA - CRUSTACEA

Concentration Factors

The accumulation of plutonium by Crustacea has been monitored in only a few animals (Table 5). The earliest research was performed using the lobster Homaris vulgaris. Ward (1966) followed the direct uptake by lobsters of plutonium from seawater and established that near equilbrium was reached in the exoskeleton and gills after 50 d of exposure. However, at 220 d the muscle, gut, and hepatopancreas were still not at steady-state conditions. Approximately 90% of the total plutonium taken up by the lobster was found in the exoskeleton, and, as would be expected, the major portion that accumulated was lost during molting.

The uptake of Pu(IV) and Pu(VI) from food and water was followed in the shrimp Lysmata seticaudata (Fowler et al., 1975). No change in uptake rate with different valence states was detected. However, the valence state of plutonium in the media was not documented during the course of the experiment. For this shrimp, direct uptake from the seawater was slow, and body burdens were reduced when molting occurred. Shrimp fed daily rations of labeled Artemia sp. for 15 d did not accumulate higher levels of plutonium than those fed a single ration of labeled Artemia sp. When feeding of nonlabeled food was resumed, the burden in the soft tissues was reduced rapidly.

Plutonium was incorporated into the hepatopancreas of the edible crab Cancer pagurus that had been fed contaminated food. Absorption of plutonium in the hepatopancreas was as high as 5%; < 0.3% was present in the hemolymph (Fowler and Guary, 1977). Investigations were conducted to determine the subcellular distribution of plutonium in the hepatopancreas of crabs that were contaminated in vivo with ^{59}Fe (Guary and Negrel, 1980). When the cytosolic

Table 5. Laboratory-derived concentration factors (CFs) for plutonium in Arthropoda - Crustacea.

Organism	Body part	Exposure, d	CFs	Comments
Lysmata seticaudata (shrimp)[a]	Whole	25	5-19	Pu(VI), water
Corophium volutator (amphipod)[b]	Whole	14	0.1	Pu(VI), sediment
C. volutator[b]	Whole	12	1000	Pu(VI), water, nonequilibrium
Homaris vulgaris (lobster)[c]	Muscle	250	3	Water

[a] Fowler *et al*. (1975).

[b] Miramand *et al*. (1982).

[c] Ward (1966).

fraction of the hepatopancreas was incubated in vitro with ^{237}Pu, approximately 20% of the plutonium was associated with compounds of molecular weight ranging from 10,000 to 40,000. The investigators proposed that these proteins could belong to the metallothionein family that has been shown to bind other heavy metals such as cadmium, copper, zinc, and mercury. About 70% of the plutonium eluted in the very low molecular weight fraction, which was below the operational range of the Sephadex G-200, and the authors suggest that this plutonium was present as free metal. The distribution of plutonium was different than that of ^{59}Fe, which was bound primarily with a soluble protein of high molecular weight ($\sim$450,000).

Elimination Rates

Limited data are available on the half-life of plutonium in Crustacea. Fowler et al. (1975) found the loss of plutonium from shrimp was most rapid when it was ingested with food. The initial rapid loss was due primarily to clearance of the gut; the slower loss was due to other excretory processes. When shrimp were exposed to plutonium in water, most was present in the exoskeleton. Consequently, molting resulted in a rapid change in the body burden and a change in the kinetics of elimination. Molts may play an important role in the biogeochemical cycling of plutonium because the CF in crustacean exoskeleton is high and plutonium in the molt is lost slowly. In those areas where the bulk of marine animal biomass is composed of small crustacea that molt frequently, cast molts may be an important mechanism for transporting plutonium to sediments as well as to detrital feeders (Fowler et al., 1976).

CHORDATA - PISCES

Concentration Factors

Laboratory-determined CFs for marine fishes are few in number; more field-determined values are available (Figs. 3 and 4). Data available were obtained by Pentreath (1978a, 1978b) who studied the uptake of ^{237}Pu (VI) by plaice (Pleuronectes platessa) and by the thornback ray (Raja clavate). The assimilation of ^{237}Pu by plaice was followed in fish exposed to the isotope in water, in fish fed ^{237}Pu-contaminated Nereis sp., and in fish injected with the radionuclide. Uptake from the water was very slow; after a 63-d uptake, the CF was <1. Of the plutonium accumulated, most of it was in the digestive tract. Plutonium was detectable in the livers of six of the seven fish used, and only traces were measurable in blood cells, plasma, and bone of two fishes.

The thornback ray, a cartilaginous fish, appeared to assimilate more ^{237}Pu than the plaice. When rays were fed Nereis sp. that had been injected with the radionuclide, and crab hepatopancreas that had been incubated with ^{237}Pu, the isotope was found consistently in the liver. In one fish, 0.2% of the administered dose was found in the liver. Also, in rays that had been injected with ^{237}Pu, there were high concentrations of the radionuclide in the spleen as well as the liver.

It is clear that the thornback ray differs from the plaice in the ability to absorb ^{237}Pu from labeled food. In comparable experiments, the plaice livers did not contain more than 0.005% of the total plutonium given in a single labeled meal, whereas the thornback ray livers contained up to 0.23% of the plutonium administered. Also, the thornback ray had a higher estimated percentage of the body burden in the skeleton than did plaice.

Elimination Rates

Data on the biological half-life of plutonium are available only for plaice (Pentreath, 1978a). The retention of ^{237}Pu by plaice fed injected Nereis sp. and then fed unlabeled Nereis sp. was determined. The half-life measured in 10 fish ranged from 9 to 49 d. When fish were injected with ^{237}Pu (IV) intramuscularly, the half-life was considerably longer; values ranged between 642 and 877 d. Similar results were obtained from fish that had been injected directly into the body cavity; half-life values ranged from 282 to 1100 d. There was marked redistribution of the isotope within fish after they were injected with the isotope. The redistribution was independent of the site of injection and resulted in the highest accumulations occurring in the liver, kidney, and spleen. Growing fish incorporated a relatively larger fraction of the ^{237}Pu body burden into skeletal material than nongrowing fish, and this was attained at the expense of the isotopic content of the liver. Very little ^{237}Pu was incorporated into muscle.

AMERICIUM

PHYSICOCHEMICAL FORM

The major source of americium to the environment is from nuclear weapon testing. It was assumed because the americium, like plutonium, was present in high-fired oxide particles that it would not dissolve in natural waters. However, experimental data from a wide variety of environments does not bear out this assumption, and americium has been reported in the soluble fraction of marine waters from a number of environments (see review of Watters *et al*., 1980).

Americium is known to form complexes that affect its physicochemical form and increase the total concentration of the metal in the water. In seawater, the most likely oxidation state is the III.

Information on the biogeochemistry of americium in marine environments indicates that most of the americium that was deposited in the ocean from atmospheric fallout and nuclear wastes was transferred to the sediments. The K_d recommended for use in models of both the pelagic and coastal region of the ocean is 2,000,000; the range recommended for sensitivity analysis is from 100,000 to 20,000,000 (IAEA, 1985). However, it appears that americium is not irreversibly retained on sediment particles, but can be released into interstitial waters and hence into the water column upon changes in the concentration of americium in the overlaying waters (Noshkin and Wong, 1980).

PRIMARY PRODUCERS

Concentration Factors

Microalgae. Americium concentration factors in marine plankton at steady-state conditions were in the same range as those for plutonium (cf. Tables 1 and 6; Figs. 3 and 5). Appreciable differences were determined with species, but cells accumulated americium in proportion to the radionuclide concentration in the water (Fisher *et al*., 1983a). The uptake by dead cells was compared to that by live cells for two species. Uptake was identical, indicating that the uptake process was passive. Uptake was not affected greatly by the presence or absence of light, changes in salinity, or the presence of other metals.

Table 6. Laboratory-derived concentration factors (CFs) for americium in primary producers (microalgae).[a]

Organism	Exposure, d	CF	Comments
Thalassiosira pseudonana	3 to 7	410,000	3H clone
Dunaliella tertiolecta	3 to 7	130,000	Dun clone
Oscillatoria woronichinii	3 to 7	7,000	OSE N4 clone
Emiliania huxleyi	3 to 7	70,000	MCH No. 1 clone
E. huxleyi	3 to 7	150,000	BT-6 clone
Tetraselmis chuii	3 to 7	50,000	Tet C2 clone
Heterocapsa pygmaea	3 to 7	280,000	Gymno clone
Monaco port particles	3 to 7	110,000	Natural assemblages
Offshore particles	3 to 7	640,000	Natural assemblages

[a] Fisher et al. (1983a).

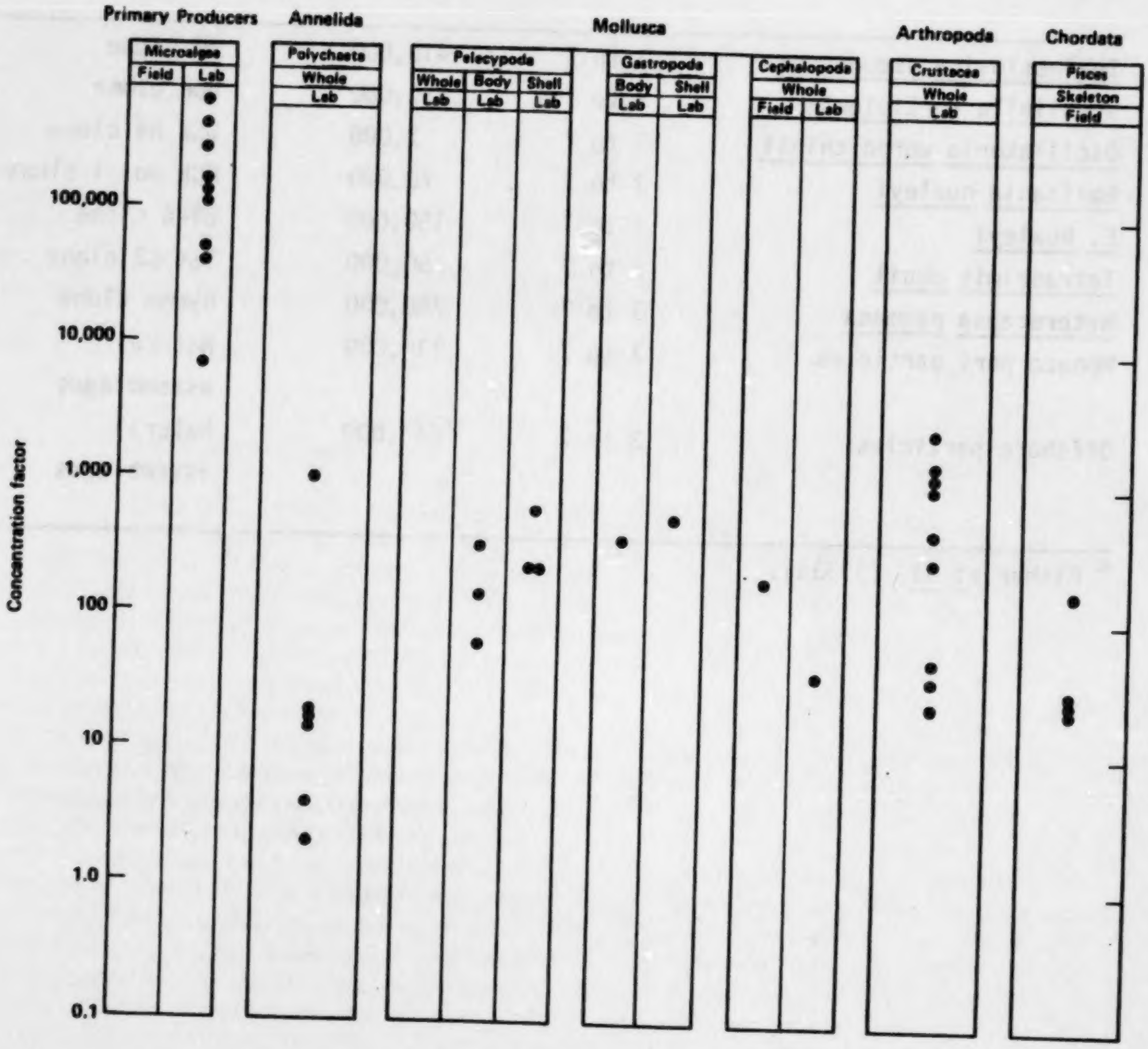

Figure 5. Concentration factors (CFs) for americium in marine biota: laboratory-derived CFs from this report (●); field-derived CFs from Noshkin (1985) (●).

However, the uptake of americium was directly proportional to the cell concentration in the water and was related to the size and surface area of the plankton. The effect of naturally occurring dissolved organic matter (DOM) on the uptake of americium by Thalassiosira pseudonana was determined (Fisher et al., 1983b). They concluded that the DOM did not appreciably affect the bioavailability of the americium. The cellular distribution of ^{241}Am was studied in two algal species: the diatom Thalassiosira pseudonana and the naked green alga Dunaliella tertiolecta (Fisher et al., 1983c). After a 72-h exposure of the algae to the isotope, 94% of the cellular ^{241}Am was found in the 745 x g and 2000 x g pellets. These data indicate that most of the ^{241}Am is associated with cell walls or membranes and does not generally bind to soluble cellular proteins.

Macroalgae. No data on laboratory-derived CFs of americium in macroalgae were available.

Elimination Rates

Microalgae. Different species of phytoplankton accumulated americium rapidly, but the time to approach steady-state conditions differed with the species; the range was from 2 to 4 d (Fisher et al., 1983a). The loss of americium was followed in two species, Thalassiosira pseudonana and Dunaliella tertiolecta (Fisher et al., 1983a). Loss curves were described by a two-compartment model with a rapid initial loss (being greater in size in short-term exposed cells) and a subsequent, more gradual loss. These investigators proposed that this probably reflected the presence of two americium compartments in the cells, with a greater fraction of cellular americium in the more rapid compartment. Biological half-lives in the rapid- and slow-elimination compartments were <1 to 1 d, and 10 to 12 d, respectively.

Macroalgae. The loss of ^{241}Am was monitored from Halimeda incrassata that had been transferred from a highly contaminated crater in the Enewetak Atoll to the lagoon, which had a relatively low level of ^{241}Am (Spies et al., 1981). The loss rate constant for the fast-exchanging compartment was 0.49 (half-life of 1.4 d) and for the slow-exchanging compartment was 0.067 (half-life of 10.3 d). These exchange rates were similar to those obtained for plutonium and europium.

ANNELIDA - POLYCHAETA

Concentration Factors

Concentration factors for americium in the same species of nereidae worms were generally higher for americium than plutonium (cf. Tables 2 and 7). Only a few values are available for the uptake of americium from seawater (Fig. 4), and these differ widely. It is not known whether the differences are due to species, analytical methods, or the absence of steady-state conditions. One potential source of variability is the presence of food or sediment in the gut of the worms. These materials generally have higher affinities for americium than worm soft tissues; varying amounts of these substances in the gut could affect the CF value obtained. Another source of variability is the physicochemical form of the americium in the water. Murray _et al_. (1978) found that the CF obtained in freshly prepared water was different from that obtained in aged water, and that the CF was also affected by the pH of the water and the partitioning of the americium between the soluble and particulate phases of the water.

The CF values were considerably lower for uptake from sediment than from water (Beasley and Fowler, 1976; Vangenechten _et al_., 1983). The values determined by Beasley and Fowler (1976) from uptake from the sediment showed an increase with increased exposure time; these were based on the dry weight of the animal and sediment.

Elimination Rates

The accumulation of americium by worms from seawater occurred rapidly; steady-state conditions of uptake and loss were reached in a few days (Beasley and Fowler, 1976; Murray _et al_., 1978; Grillo _et al_., 1981; Miramand _et al_., 1982). Grillo _et al_. (1981) followed the loss of ^{241}Am from the polychaete _Hermione hystrix_. Analysis of the loss curves indicated the presence of at least two distinct compartments within the worm. A long-lived compartment was identified that contained about 60% of the activity, and radioactivity from this compartment was eliminated with a biological half-life of 66 d (calculated for the period between the 15th and 50th day). From the smaller short-lived compartment, radioactivity was eliminated with a half-life of 6 to 7 d.

Table 7. Laboratory-derived concentration factors (CFs) for americium in Annelida - Polychaeta.

Organism	Body part	Exposure, d	CFs	Comments
Nereis diversicolor[a]	Whole[b]	5	0.0012	Am in sediment
N. diversicolor[a]	Whole[b]	15	0.002	Am in sediment
N. diversicolor[a]	Whole[b]	40	0.0024	Am in sediment
N. diversicolor[a]	Whole	225	0.004	Am in sediment
Hermione hystrix[c]	Whole	22	1000	Am in seawater
H. hystrix[c]	Body wall	22	1900-2200	Am in seawater
H. hystrix[c]	Setae	22	8000-13,000	Am in seawater
Arenicola marina[d]	Whole	14	2000-3000	Am in sediment
A. marina[d]	Whole	21	18	Am in seawater
Nereis diversicolor[e]	Whole	20	2-4	Am in aged seawater
N. diversicolor[e]	Whole	20	16-21	Am in fresh seawater
Hermione hystrix[f]	Whole	40-50	0.05-0.12	Am in sediment

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[a] Beasley and Fowler (1976).

[b] Calculated from the dry weight of worm and sediment.

[c] Grillo *et al*. (1981).

[d] Miramand *et al*. (1982).

[e] Murray *et al*. (1978).

[f] Vangenechten *et al*. (1983).

MOLLUSCA

Concentration Factors

Pelecypoda. Americium CFs are available for three species of bivalve molluscs (Table 8). The CFs differed with species and body part (Grillo et al., 1981; Miramand et al., 1982; Vangenechten et al., 1983). Most of the activity was associated with the shell, and steady-state conditions of uptake and loss were not reached. In Tapes decussatus, the uptakes of americium and plutonium were followed simultaneously in the same animals. At the end of the 3-wk exposure, plutonium was accumulated to a lesser extent than americium. However, because steady-state conditions were not reached, it can not be concluded that this same relationship would continue with time. In Scrobicularia plana, accumulation from seawater and sediments was determined independently. The CFs calculated from the sediments were lower than those from the water. However, if the concentration of americium in the interstitial water of the sediments instead of the concentration of the sediments is used in the calculation, the CFs are more similar to those obtained with the americium in the seawater. No field-derived CFs are available for Pelecypoda (Figs. 5 and 6).

Gastropoda. Data on the accumulation of americium by gastropod molluscs are available for only Aporrhais pespelicani (Grillo et al., 1981). The CF values obtained and the kinetics of bioaccumulation were similar to those for the clam Tapes decussatus. In this organism also, the uptakes of americium and plutonium were followed simultaneously in the same animals. Similar to T. decussatus, the CFs for americium after the 3-wk exposure were higher than those for plutonium.

Cephalopoda. CFs were determined for the cephalopod Octopus vulgaris (Table 8). The animals were exposed to americium and plutonium concurrently for 15 d. Examination of the accumulation curves for both elements showed that equilibrium had not been reached. Accumulation of plutonium appeared to be more rapid than that of americium; after 2 weeks the whole-body CFs were 35 for americium and 65 for plutonium. CFs for both elements were high in the gills, but the highest CFs were found in the branchial hearts and appendages (7100 for americium compared to 9300 for plutonium). In the branchial hearts, the

Table 8. Laboratory-derived concentration factors (CFs) for americium in Mollusca.

Organism	Body part	Exposure, d	CFs	Comments
		Pelecypoda		
Tapes decussatus[a] (clam)	Shell	20	500	Am in seawater
T. decussatus[a]	Body	20	330	Am in seawater
T. decussatus[a]	Muscle	20	30	Am in seawater
Scrobicularia plana[b] (clam)	Whole	14	0.009	Am in sediment
S. plana[b]	Shell	14	0.01	Am in sediment
S. plana[b]	Body	14	0.01	Am in sediment
S. plana[b]	Shell	14	228	Am in interstitial water
S. plana[b]	Body	14	137	Am in interstitial water
S. plana[b]	Shell	32	220	Am in seawater
S. plana[b]	Body	32	60	Am in seawater
Venerupis decussata[c] (clam)	Whole	40-50	0.004-0.02	Am in sediment
		Gastropoda		
Aporrhais pespelicani[a] (snail)	Shell	20	580	Am in seawater
A. pespelicani[a]	Body	20	330	Am in seawater
		Cephalopoda		
Octopus vulgaris[d] (octopus)	Whole	15	35	Am in seawater
O. vulgaris[d]	Muscle	15	33	Am in seawater

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[a] Grillo et al. (1981).

[b] Miramand et al. (1982).

[c] Vangenechten et al. (1983).

[d] Guary and Fowler (1982).

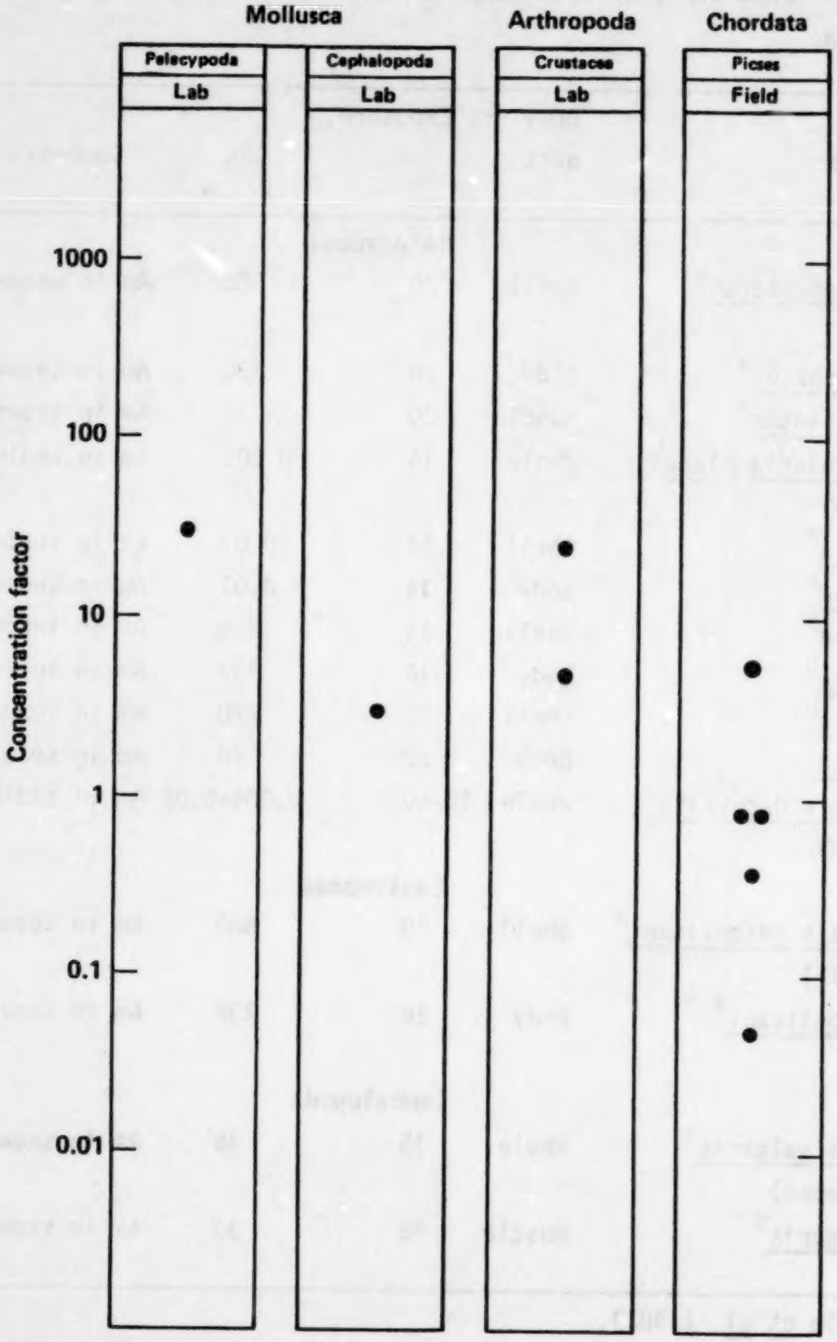

Figure 6. Concentration factors (CFs) for americium in muscle tissue of marine biota: laboratory-derived CFs from this report (●); field-derived CFs from Noshkin (1985) (●).

radionuclides are associated with granular pigment deposits or adenochromes that occur in the cells and may be important in detoxication processes (Miramand and Guary, 1981).

When contaminated food is ingested, americium is efficiently assimilated (mean = 33%) into the tissues of the octopus (Guary and Fowler, 1982). These investigators state that this assimilation coefficient is of the same order of magnitude as that measured for plutonium in crabs (Fowler and Guary, 1977) but is 30 times higher than coefficients for plutonium in fish (Pentreath, 1978a, b) and 300 to 3000 times those of transuranic nuclides in mammals. Guary and Fowler (1982) proposed that the high degree of assimilation of americium may be linked to the high food-conversion efficiency reported for _O. vulgaris_.

Elimination Rates

Pelecypoda. Data on the biokinetics of americium in bivalve molluscs are available for the clam _Tapes decussatus_ and for the mussel _Mytilus galloprovincialis_ (Table 9). In the clam, at least two distinct compartments that were eliminated at substantially different rates were found. Radioactivity in the short-lived compartment had a half-life of 6 d and in the long-lived compartment, 80 d.

Biological half-lives of americium were determined in mussels that had been exposed to ^{241}Am in the laboratory and then transferred to small cages anchored in the littoral zone off Monaco (Guary and Fowler, 1981). Loss of ^{241}Am was described as the sum of three exponential functions. Two short-lived compartments were identified. These represented a total of 80% of the incorporated radionuclide and had half-lives of 2 and 3 wk. The remaining fraction of ^{241}Am was associated with a long-lived compartment that was lost very slowly (half-life of 1.3 y). Loss rates of americium differed with body part, with the most rapid occurring in gill, viscera, and shell. Some indication of translocation of ^{241}Am from other tissues to the mantle and muscle during depuration was obtained.

Gastropoda. In the gastropod _Aporrhais pespelicani_, americium was lost at rates comparable to those of the clam _T. decussatus_ (Grillo _et al_., 1981). Two compartments were identified, one that contained about 65% of the

Table 9. Biological half-life (days) of americium in Mollusca.[a]

Organism	Pool A	Pool B	Pool C	Comments
	Pelecypoda			
Tapes _decussatus_ (clam)[b]	80(55-65)	6(35-45)	--	Am in seawater
Mytilus _galloprovincialis_[c] (mussel)	480(25)	22(40)	11(40)	Am in seawater
	Gastropoda			
Aporrhais _pespelicani_[b] (snail)	80(65)	6(30)	--	Am in seawater
	Cephalopoda			
Octopus _vulgaris_[d] (octopus)	560(46)	2(30)	--	Am in seawater

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[a] Number in parentheses is the percent of total activity in the pool.

[b] Grillo _et_ _al_. (1981).

[c] Guary and Fowler (1981).

[d] Guary and Fowler (1982).

incorporated radionuclide and in which elimination was very slow, and another that represented about 30% of the radioactivity and in which elimination was rapid.

Cephalopoda. Data on the loss of americium are available for O. vulgaris (Guary and Fowler, 1982). Whole body loss occurred with two compartments. The short-lived compartment, which contained about 30% of the initial activity, turned over very rapidly; half-life of about 2 d. Radioactivity in the long-lived compartment had a half-life of 560 d. These investigators proposed that the short-lived compartment could represent principally the skin, which eliminated the radionuclide very rapidly, whereas the long-lived compartment could represent the branchial hearts, which lost the radioactivity very slowly.

ARTHROPODA - CRUSTACEA

Concentration Factors

One of the early studies of the uptake of americium in crustaceans was performed on brine shrimp and euphausiids by Fowler and Heyrand (1974). A higher CF was obtained for the brine shrimp Artemia sp. than for the euphausiid Meganyctiphanes norvegica (Table 10). A short-term experiment was performed with Artemia sp. to determine uptake of ^{241}Am from a labeled population of phytoplankton. Uptake from the food appeared to be less efficient than that from seawater; a CF of 400 was reached with the tracer in the food and of 1700 with the tracer in the seawater. Filtration of the seawater showed that most of the ^{241}Am was associated with the phytoplankton. When the CF was calculated from the concentration of ^{241}Am in the seawater in which the phytoplankton were suspended, a CF similar to that obtained from the water alone was calculated. The authors concluded that little americium was accumulated from the food.

The accumulation of americium was followed also in the brackish-water amphipod Gammarus duebeni and the harpacticoid copepod Tisbe holothuriae (Murray et al., 1978). The CF was affected significantly by the physicochemical form of the ^{243}Am in the water; aging of the water before the addition of the organisms reduced the CF values obtained. The uptake by G. duebeni of ^{243}Am from contaminated food was followed for 10 d. Unlike the uptake from the water alone, the uptake of ^{243}Am steadily increased; steady-state conditions were not reached in the course of the experiment.

Table 10. Laboratory-derived concentration factors (CFs) for americium in Arthropoda - Crustacea.

Organism	Body part	Exposure, d	CFs	Comments
Artemia sp.[a] (brine shrimp)	Whole	48	1700	Am in seawater
Meganyctiphanes norvegica[a] (euphausiid)	Whole	64	125	Am in seawater
Crab or Lobster[b]	Muscle	8	5	Am in seawater
Crab or Lobster[b]	Muscle	8	25	Am in seawater
Gammarus duebeni[c] (amphipod)	Whole	12 to 16	25-56	Am in aged seawater
Corophium volutator[d] (amphipod)	Whole	14	0.12	Am in sediment
C. volutator[d]	Whole	14	1200	Am in seawater
C. volutator[d]	Whole	14	2700	Am in interstitial waters of sediment
Gammarus duebeni[e] (amphipod)	Whole	10	300	Am in seawater
G. duebeni[e]	Whole	10	40	Am in aged seawater
Tisbe holothuriae[e] (copepod)	Whole	7	1070	Am in seawater
Cirolana borealis[f] (isopod)	Whole	40-50	0.006-0.032	Am in sediment

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[a] Fowler and Heyrand (1974).

[b] Guary (1980), cited from Jackson *et al*. (1983).

[c] Hoppenheit *et al*. (1980).

[d] Miramand *et al*. (1982).

[e] Murray *et al*. (1978).

[f] Vangenechten *et al*. (1983).

Elimination Rates

Biokinetics of americium in Crustacea have been determined for a number of species. The early work of Fowler and Heyrand (1974) did not provide a value of biological half-life, but the authors report that accumulation was rapid. In the brine shrimp *Artemia sp.*, steady-state conditions were reached in 48 h; in the euphausiid *Meganyctiphanes norvegica*, steady-state conditions were reached in 64 h. When a single euphausiid that had accumulated ^{241}Am was placed in unlabeled seawater, it lost 40% of its burden during the first 8 d. When the animal molted, it lost almost all of its activity.

Guary (1980) determined the elimination of americium in a number of decapod crustaceans (Table 11). Elimination was rapid, and only one compartment was identified.

CHORDATA - PISCES

Concentration Factors

No data on CFs are available for fishes that were exposed to americium in the laboratory. However, CFs are reported for tissues from fish exposed to americium under field conditions (see reviews of Jackson *et al*., 1983 and Noshkin, 1985). In muscle tissue, the CF values reported ranged from 0.05 to 5 (Fig. 6), in liver from 74 to 104, and in the skeleton from 25 to 178 (Fig. 5).

Elimination Rates

No data on biological half-life of americium in fishes were found.

CESIUM

PHYSICOCHEMICAL FORM

Cesium, like other alkali metals, exists primarily as free ions and does not form inorganic complexes. In solution, it behaves like potassium, which is present in greater abundance than cesium and serves as a nonisotopic carrier element. The concentration of cesium in surface and deep seawater is 0.3 µg/kg

Table 11. Biological half-life (days) of americium in whole Arthropoda - Crustacea.[a,b]

Organism	Pool	Comments
Prawn or shrimp	45(100)	Am in seawater
Prawn or shrimp	5(100)	Am in seawater
Prawn or shrimp	8(100)	Am in food
Prawn or shrimp	2(100)	Am in food
Prawn or shrimp	3(100)	Am in food
Prawn or shrimp	5(100)	Am in food
Prawn or shrimp	20(100)	Am in food

[a] Number in parentheses is the percent of total activity in the pool.
[b] Guary (1980), quoted from Jackson _et_ _al_. (1983).

and 0.3 mg/kg, respectively, and that of potassium is 399 mg/kg for both areas (Quinby-Hunt and Turekian, 1983). Because cesium sorbs to particulate material, especially clays, it is present in higher concentration in sedimentary material. The mean and range of distribution coefficients, K_ds, recommended for use in models of pelagic waters are 2,000 and from 500 to 20,000; recommended mean and range K_ds for models of coastal waters are 3,000 and from 100 to 20,000, respectively (IAEA, 1985). Because the K_d for cesium is relatively low, stable and radioactive nuclides of cesium in marine ecosystems are primarily in the water column as soluble, ionic forms, and they behave conservatively.

PRIMARY PRODUCERS

Concentration Factors

Concentration factors for cesium in primary producers are generally low (Table 12). Because of the chemical similarities and relative abundances of cesium and potassium concentrations in the water, potassium serves as a nonisotopic carrier for cesium. Comparison of the CFs determined for field and laboratory populations for radioactive cesium and stable cesium shows that the ranges overlap except for the field-determined values for microalgae (Fig. 7).

The uptake of cesium by killed cells of Ulva lactuca gave CF values of 1-2 (Gutknecht, 1965). Also, seaweeds that had been exposed to ^{137}Cs for up to 35 d released more than 90% of their activity when killed and kept for several hours in the same radioactive medium. This investigator concluded that neither physical adsorption, adsorption exchange, nor nonexchangeable binding could account for much of the ^{137}Cs taken up by the seaweeds examined.

The effect of external cesium concentration on cesium uptake was examined in Gracilaria foliifera, Fucus vesiculosus, Ulva lactuca, and Porphyra umbilicus (Gutknecht, 1965). A plot of log cesium uptake vs log external cesium concentration was linear, indicating that uptake was exactly proportional to external concentration. This investigator stated that these results are consistent with the data indicating that ^{137}Cs in seaweeds is mainly ionic and not extensively adsorbed.

Cesium uptake was stimulated by light in all species examined (Gutknecht, 1965). This was first observed by Scott (1954), who suggested a connection between the mechanisms of cesium accumulation and photosynthesis.

Table 12. Laboratory-derived concentration factors (CFs) for cesium in primary producers.

Organism	Exposure, d	CFs	Comments
	Microalgae		
Nitzschia closterium[a]	13	1.2	---
Amphora sp.[a]	13	1.5	---
Nitzschia sp.[a]	13	1.7	---
Chlamydomonas sp.[a]	13	1.3	---
Chlorella sp.[a]	13	2.4	---
Pyramimimonas sp.[a]	13	2.6	---
Nannochloris atomus[a]	13	3.1	---
	Macroalgae		
Ulva sp. (green alga)[b]	74	3,4	Sulfate form
Enteromorphia sp. (green alga)[b]	31	4	Sulfate form
Fucus serrata (brown alga)[b]	31	6	Sulfate form
F. serrata[b]	153	16	Sulfate form
F. serrata[b]	44	4	Sulfate form
Chrondrus crispus (red alga)[b]	74	4,10,19	Sulfate form
C. crispus[b]	107	10-15	Sulfate form
Corallina sp. (red alga)[b]	74	8,9,13,13,14	Sulfate form
Chrondus crispus (red alga)[c]	100-200	10-20	---
Acetabularia mediterranea[d] (green alga)	13	13	Effluent a
A. mediterranea[d]	13	1	Effluent b
A. mediterranea[d]	14	1-2	Effluent c
A. mediterranea[d]	3-7	<1	Effluent d
A. peniculus[d]	17	<1-4	Effluent c
A. peniculus[d]	3	<1	Effluent d
Batophora oerstedii[d]	13	11,18	Effluent a
B. oerstedii[d]	19	1-2	Effluent e
Boergesenia forbesii[d]	13	6	Effluent a

Table 12. (Continued).

Organism	Exposure, d	CFs	Comments
B. forbesii[d]	19	~1	Effluent b
B. forbesii[d]	3	<1	Effluent d
Fucus serratus (brown alga)[d]	8	2	Effluent d
Porphyra sp. (red alga)[d]	6	4-7	Effluent d
Ulva lactuca (green alga)[d]	8	24-28	Effluent d
Porphyridium curentum (red alga)[a]	13	1.3	---
Ulva lactuca (green alga)[e]	35	7	---
Codium decorticatum (green alga)[e]	35	4	---
Fucus vesiculosus (brown alga)[e]	35	30	---
Dictyota dichotoma (brown alga)[e]	35	10	---
Porphyra umbilicalis (red alga)[e]	35	5	---
Chondrus crispus (red alga)[e]	35	30	---
Gracilaria foliifera (red alga)[e]	35	2.5	---
Agardhiella tenera (red alga)[e]	35	6	---
Hypnea musciformis (red alga)[e]	35	11	---
Monostroma sp. (green alga)[f]	1	1.2	---
Scytosiphon lomentarium (brown alga)[f]	1	2	---
Gracilaria confervoides (red alga)[f]	1	1.6	---
Ulva ridiga (green algae)[g]	64	4-10	---
Cystoseira barbata (brown alga)[g]	64	30	---
Sargassum natans (brown alga)[h]	32	3.7	---
S. fluitans[h]	32	10.2	---
Green alga[i]	26	3.4 ± 0.2	---
Green alga[i]	26	1.8 ± 0.0	---
Green alga[i]	26	1.6 ± 0.0	---
Brown alga[i]	26	10 ± 0.6	---
Brown alga[i]	26	11.5 ± 0.6	---
Brown alga[i]	26	2.9 ± 0.2	---
Red alga[i]	26	3.8 ± 0.0	---
Red alga[i]	26	6.3 ± 0.4	---
Red alga[i]	26	4.9 ± 0.2	---
Red alga[i]	26	3.9 ± 0.2	---

Table 12. (Continued).

Organism	Exposure, d	CFs	Comments
Fucus vesiculosus (brown alga)[j]	45	50	Sulfate form
Cyrtymenia sp. (red alga)[k]	11	5	---

[a] Boroughs *et al*. (1957).

[b] Ancellin and Vilquin (1968).

[c] Avarques *et al*. (1968).

[d] Bonotto *et al*. (1981).

[e] Gutknecht (1965).

[f] Hiyama and Shimizu (1964).

[g] Polikarpov (1961).

[h] Polikarpov (1964).

[i] Ryndina (1972), cited from Jackson *et al*. (1983).

[j] Scott (1954).

[k] Ueda *et al*. (1978).

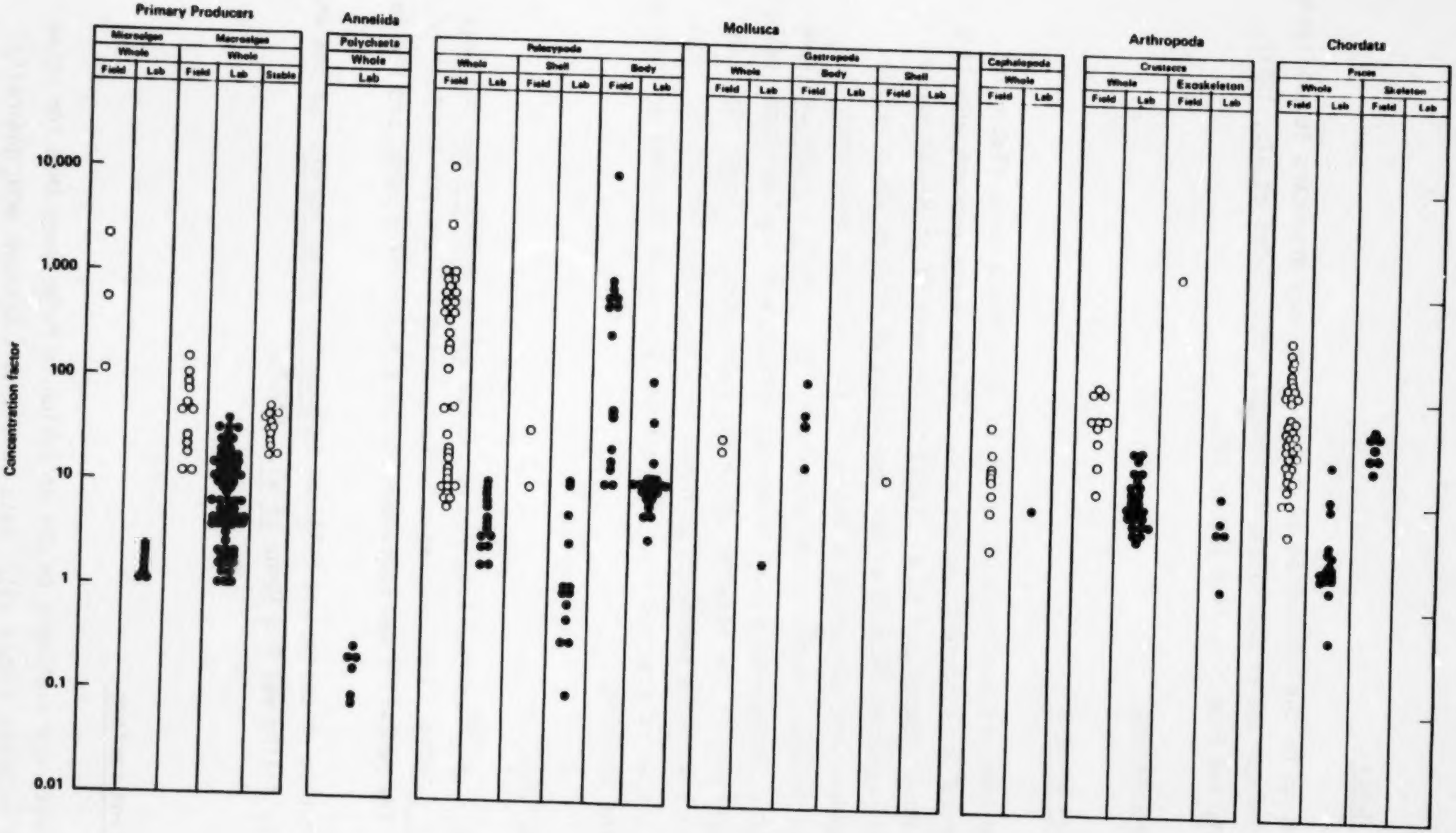

Figure 7. Concentration factors (CFs) for cesium in marine biota: laboratory-derived CFs from this report (•); field-derived CFs from Noshkin (1985) (•), field-derived data from Jackson et al. (1983) (o); stable-element-derived CFs from Polikarpov (1966) (o).

Elimination Rates

Information on the metabolism of cesium in primary producers is available for only a few species of macroalgae (Gutknecht, 1965; Spies *et al*., 1981). Half-lives ranged from 2 to 21 d (Table 13).

ANNELIDA - POLYCHAETA

Concentration Factors

Limited data are available on cesium for polychaete worms (Table 14). Values reported for different species were < 10 for worms exposed only 11 d as well as those exposed for 58 d. Rapid achievement of steady-state conditions is expected because of the small size of most marine annelids.

Experiments were conducted to determine the relative importance of sediment and seawater on the accumulation of ^{137}Cs by *Nereis japonica* (Ueda *et al*., 1977). Worms were placed in direct contact with contaminated sediments and also suspended in the seawater above the sediments. Although those in direct contact with the sediments acquired greater concentrations of ^{137}Cs, the amount the worms acquired from the seawater was about 30 times greater than that from the sediments.

Elimination Rates

The loss of ^{137}Cs from both fed and unfed *Nereis japonica* was followed (Ueda *et al*., 1977). The loss was relatively rapid and similar for both groups of worms. The half-life was calculated to be 6 d for unfed worms and 8 d for fed worms.

Elimination of cesium was followed in *Neanthes diversicolor*. In the whole worm, the half-life was 8 d (Ueda *et al*., 1976).

MOLLUSCA

Concentration Factors

More data are available on CFs of cesium in Pelecypoda than for other classes of Mollusca (Table 15). Data on the soft tissues were generally

Table 13. Biological half-life (days) of cesium in primary producers (macroalgae).

Organism	Pool[a]	Comments
Ulva lactuca (green alga)[b]	5	--
Codium decorticatum (green alga)[b]	15	--
Fucus vesiculosus (brown alga)[b]	8	--
Porphyra umbilicalis (red alga)[b]	3	--
Chondrus crispus (red alga)[b]	2	--
Gracilaria foliifera (red alga)[b]	12	--
Agardhiella tenera (red alga)[b]	21	--
Halimeda incrassata (calcareous alga)[c]	3	--

[a] The percent of the total activity in the pool is 100.

[b] Gutknecht (1965).

[c] Spies (1981).

Table 14. Laboratory-derived concentration factors (CFs) for cesium in Annelida - Polychaeta.

Organism	Exposure, d	CFs	Comments
Arenicola marina[a]	21	2-3	Nonequilibriun
A. marina[a]	21	4-5	From sediment
Nereis diversicola[b]	58	7.5	---
N. diversicola[b]	33	6.3	---
N. japonica[c]	11	6 ± 1	From water
N. japonica[c]	11	5	From food and water
N. japonica[c]	11	0.16	From sediment
N. japonica[d]	11	0.2	From sediment
N. japonica[d]	14	0.18	From sediment

[a] Amiard-Triquet (1975).

[b] Bryan (1963).

[c] Ueda et al. (1977).

[d] Ueda et al. (1978).

Table 15. Laboratory-derived concentration factors for cesium in Mollusca.

Organism	Body part	Exposure, d	CFs	Comments
	Pelecypoda			
Scrobicularia plana[a] (clam)	Body	21	8.2	--
S. plana[a]	Body	21	8.9	From sediment
S. plana[a]	Shell	21	2.6	--
S. plana[a]	Shell	21	1	From sediment
Macoma balthica[a]	Body	21	7.1	--
M. balthica[a]	Shell	21	0.5	--
Chlamys operculata (clam)[b]	Flesh	21	8,14	Sulfate form
C. operculata[b]	Shell	44	0.7,0	Sulfate form
Tapes sp. (clam)[b]	Flesh	74	11	Sulfate form
Tapes sp.[b]	Shell	31	0.9	Sulfate form
Cardium edulis (clam)[b]	Flesh	100-200	10	Sulfate form
C. edulis[b]	Shell	100-200	0.3	Sulfate form
Mytilus edulis[b] (mussel)	Flesh	100-200	10-11	Sulfate form
M. edulis[b]	Shell	100-200	0.3-5	Sulfate form
Gyphaea ang.[b]	Flesh	44	8	Sulfate form
Gyphaea ang.[b]	Shell	44	0	Sulfate form
Mytilus galloprovincialis[c] (mussel)	Whole	4	4.3-6.4	--
M. edulis[d]	Body	100-200	10	--
Chlamys sp. (clam)[d]	Body	100-200	10-15	--
Tapes sp. (clam)[d]	Body	100-200	10	--
Tapes sp.[d]	Shell	100-200	1	--
M. edulis[e]	Whole	26	3	--
M. edulis[f]	Foot	22	7.8	--
M. edulis[f]	Body	22	8.5	--
M. edulis[f]	Shell	22	0.09	--
M. edulis[f]	Foot	47	8.5	--
M. edulis[f]	Body	47	10	--
M. edulis[f]	Foot	54	9.1	--
M. edulis[f]	Body	54	10.5	--
M. edulis[f]	Adductor muscle	27	8.4	--

Table 15. (Continued).

Organism	Body part	Exposure, d	CFs	Comments
	Pelecypoda (continued)			
M. edulis[f]	Retractor muscle	27	9.8	--
M. edulis[f]	Adductor muscle	58	7.8	--
M. edulis[f]	Retractor muscle	58	8.8	--
M. edulis[f]	Whole	58	12.9	--
M. edulis[f]	Body	58	9.2	--
Crassostrea gigas[g] (oyster)	Whole	48	7.7	--
C. gigas[g]	Body	48	9.4	--
C. gigas[g]	Shell	48	9.2	--
C. gigas[g]	Muscle	48	6.6	--
Mya arenaria (clam)[h]	Whole	200	4.6	--
M. arenaria[h]	Body	200	3.0	--
M. arenaria[h]	Muscle	200	10.0	--
Paphia philippinarum[i] (clam)	Body	5	7-9	--
P. philippinarum[i]	Muscle	5	∿9	--
Mya truncata (clam)[j]	Whole	28	3.5	--
Mytilus edulis (mussel)[j]	Whole	28	2.3	--
Ostrea edulis (oyster)[j]	Whole	28	1.7	--
Pecten maximus (scallop)[j]	Whole	28	1.7	--
Mytilus galloprovincialis[k] (mussel)	Shell	64	0	--
M. galloprovincialis[k]	Body	64	10	--
M. galloprovincialis[k]	Whole	64	3	--
Bivalve[l]	Whole	32	10.5	--
Bivalve[l]	Body	--	97	--
Bivalve[l]	Shell	--	0	--
Mercenaria mercenaria[m] (clam)	Body	20	6	Nonequilibrium
Crassostrea virginica[m] (oyster)	Body	12	5	--

Table 15. (Continued).

Organism	Body part	Exposure, d	CFs	Comments
	Pelecypoda (continued)			
Gomphina melanaegis[n] (clam)	Body	14	7	--
G. melanaegis[n]	Muscle	14	6	--
Rangia cuneata[o]	Whole	29	2.3	Estuarine
	Gastropoda			
Littorina littorina[j] (snail)	Whole	28	2	--
	Cephalopoda			
Octopus vulgaris[p] (octopus)	Whole	14	6	--
O. vulgaris[p]	Arms and tentacles	14	6.4	--

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[a] Amiard-Triquet (1975).

[b] Ancellin and Vilquin (1968).

[c] Argiero et al. (1966).

[d] Avargues et al. (1968).

[e] Bonotto et al. (1981).

[f] Bryan (1963).

[g] Cranmore and Harrison (1975).

[h] Harrison (1973).

[i] Hiyama and Shimizu (1964).

[j] Morgan (1964).

[k] Polikarpov (1961), cited from Jackson et al. (1983).

[l] Polikarpov (1964), cited from Jackson et al. (1983).

[m] Price (1965), cited from Jackson et al. (1983).

[n] Ueda et al. (1978).

[o] Wolfe and Coburn (1970).

[p] Suzuki et al. (1978).

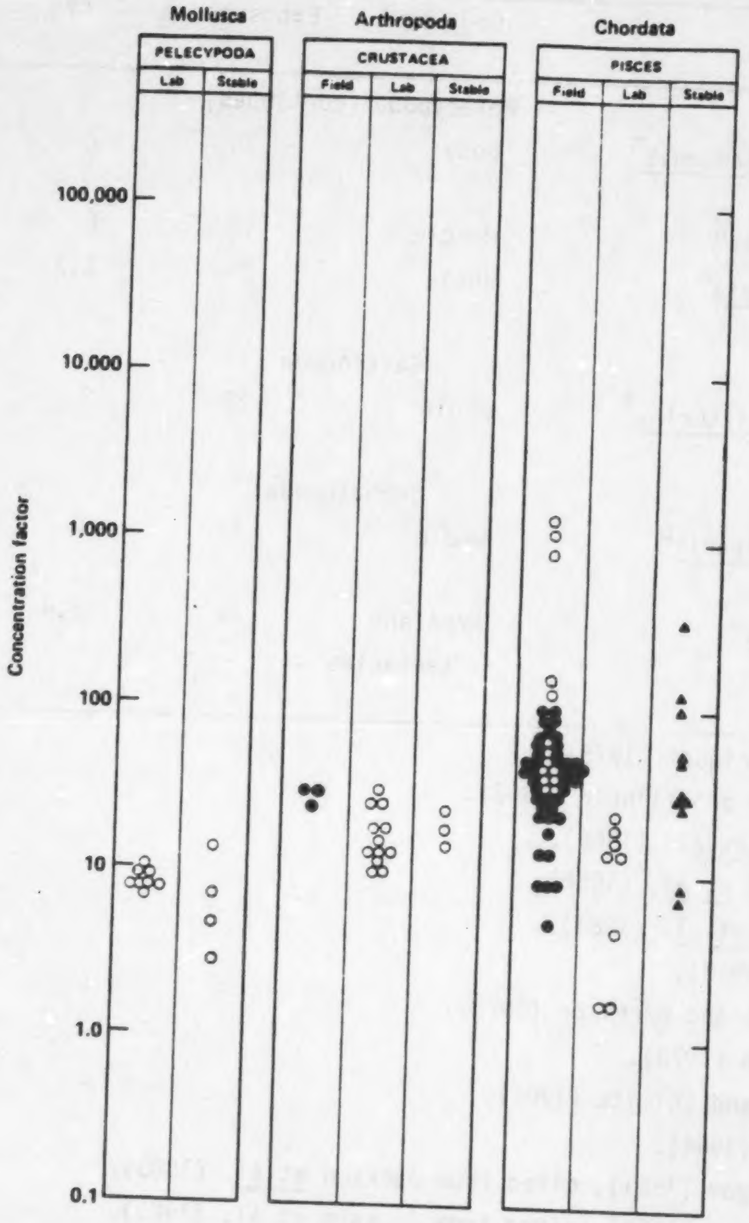

Figure 8. Concentration factors for cesium in muscle tissue of marine biota: laboratory-derived CFs from this report (o); field-derived CFs from Jackson _et al_. (1983) (o) or Noshkin (1985) (●); stable element-derived CFs from Polikarpov (1966) (o) or Pentreath, 1977 (▲).

similar to those for muscle and indicate little bioconcentration of cesium. Shell CFs were lower than those for living tissues, as expected. Comparison of field-derived and laboratory-derived data shows that the highest values were determined generally in field populations (Fig. 7).

Elimination Rates

Elimination rates of cesium have been determined for the oyster *Crassostrea gigas*, the clam *Mya arenaria*, *Gomphina melanaegis*, and *Anadara granosa*, and the mussel *Mytilus edulis* (Table 16). Two compartments were identified in some species. The biological half-life for the short-lived one was generally a few days while that for the long-lived one was generally a few months. In the octopus, cesium in the arms and tentacles, which make up 68% of the body weight, had a half-life of 90 d (Suzuki *et al*., 1978).

ARTHROPODA - CRUSTACEA

Concentration Factors

The range of CFs of cesium for Crustacea was similar to that for other marine organisms (Table 17, Figs. 7 and 8). Again, some of the highest values were obtained from Crustacea from field populations.

Elimination Rates

The only data available for elimination rates of cesium in Crustacea are for a euphausiid and a prawn. Fowler *et al*. (1971) found the half-life of ^{137}Cs in whole *Euphausia pacifica* to be 6 d. This zooplankton had been fed radioactive *Artemia sp.* nauplii. Bryan and Ward (1962) followed the loss of cesium in the prawn *Palaemon serratus*, which had acquired ^{137}Cs through the food chain. They found an average retention in three animals of about 70% of initial body burden after 48 h in nonradioactive water, and a retention of about 45% in one prawn after 6 d in nonradioactive water.

Table 16. Biological half-life (days) of cesium in Mollusca.[a]

Organism	Body part	Pool A	Pool B	Comments
		Pelecypoda		
Crassostrea gigas[b] (oyster)	Whole	90(--)	9.8(--)	--
Mytilus edulis[c] (mussel)	Whole	7.6(49)	--	--
Mya arenaria (clam)[d]	Whole	3.6(75)	60(25)	--
M. arenaria[d]	Body	3.6(77)	41(23)	--
M. arenaria[d]	Muscle	3.3(65)	33(35)	--
C. virginica[e]	Whole	250(100)		--
Anadara granosa[f] (clam)	Whole	3.0(70)	15.5(30)	--
A. granosa[f]	Whole	620.5(100)	--	Loss *in situ*
Clam[g]	Body	3(100)	--	--
Clam[g]	Muscle	13(100)	--	--
		Cephalopoda		
Octopus vulgaris (octopus)	Whole	90(100)	--	--

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[a] Number in parentheses is the percent of the activity in the pool.

[b] Cranmore and Harrison (1975).

[c] Dahlgaard (1981).

[d] Harrison (1973).

[e] Hess *et al*. (1977).

[f] Patel *et al*. (1978).

[g] Price (1965), cited from Jackson *et al.* (1983).

[h] Suzuki *et al*. (1978).

Table 17. Laboratory-derived concentration factors (CFs) for cesium in Arthropoda - Crustacea.

Organism	Body part	Exposure d	CFs	Comments
Crangon vulgaris (shrimp)[a]	Whole	12	20	--
Carcinus maenas (crab)[a]	Whole	7	4	--
C. maenas[b]	Whole	67	8.5 ± 0.6	--
C. maenas[b]	Muscle	67	17.7	--
Portunus puber (crab)[b]	Whole	67	6.6 ± 1.48	--
P. puber[b]	Muscle	67	13.1	--
P. depurator[b]	Whole	67	6.5 ± 0.0	--
P. depurator[b]	Muscle	67	12.0	--
Polybius henslowi (crab)[b]	Whole	67	5.2	--
Cancer pagurus (crab)[b]	Whole	67	6.0 ± 1.4	--
C. pagurus[b]	Muscle	67	11.3	--
Corystes cassivelaunus[b] (crab)	Whole	67	4.4	--
C. cassivelaunus[b]	Muscle	67	11.4	--
Homarus vulgaris (lobster)[c]	Whole	28	4.7	--
Decapoda-Stomatopoda[d]	Muscle	58	19.4	--
Zooplankton[d]	Whole	--	12	--
Zooplankton[d]	Whole	--	14	--
Galathea squamifera[e] (squat lobster)	Muscle	11	12.6, 13.6	--
G. squamifera[e]	Exoskeleton	11	4.0, 4.2	--
H. vulgaris[f]	Whole	150	7.6	--
H. vulgaris[f]	Muscle	150	14.9	--
H. vulgaris[f]	Exoskeleton	150	1.5	--
Palaemon serratus[f]	Whole	4.2	29.2	Water, unfed
P. serratus[f]	Muscle	4.2	33.9 ± 2.6	Water, unfed
P. serratus[f]	Shell	4.2	10.9 ± 4.5	Water, unfed
P. serratus[f]	Whole	4.2	25	Food and Water
P. serratus[f]	Muscle	4.2	25.6 ± 1.6	Food and Water
P. serratus[f]	Whole	4.2	29.5	Food and Water

Table 17. (Continued).

Organism	Body part	Exposure d	CFs	Comments
P. serratus[f]	Muscle	4.2	27.4 ± 2.0	Food and Water
P. serratus[f]	Shell	4.2	6.6 ± 1.2	Food and Water
Leander pacificus[g]	Whole	11	13.3 ± 2.6	--
L. pacificus[g]	Body	4	15	--
L. pacificus[g]	Body	2	15	--
Shrimp or prawn[h]	Whole	150	12-13	--
Crangon vulgaris (shrimp)[c]	Whole	28	20	--
Pandalus montagui (shrimp)[c]	Whole	28	18	--
Leander serratus (shrimp)[c]	Whole	8	15.9	--
Nephrops norvegicus[c] (euphausiid)	Whole	28	7.3	--
Cancer pagurus (crab)[c]	Whole	28	7.2	--

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[a] Bonotto et al. (1981).

[b] Bryan (1961).

[c] Morgan (1964).

[d] Bryan (1963), cited from Jackson et al. (1983).

[e] Bryan (1965).

[f] Bryan and Ward (1962).

[g] Hiyama and Shimizu (1964).

[h] Lemee et al. (1970), cited from Jackson et al. (1983).

CHORDATA - PISCES

Concentration Factors

Considerable data are available on CFs of cesium for marine fishes (Table 18). CF values for fishes are similar in range to those of other aquatic organisms (Figs. 7 and 8). A number of studies have been undertaken to try to understand the effect of route of entry of the cesium radionuclides on CFs and to ascertain whether trophic enrichment occurs (higher CFs in organisms in higher trophic levels than in those in lower trophic levels). Data are not available that permit conclusions to be made on the effects of feeding behavior and trophic level on CF values (see review by Pentreath, 1981).

Factors affecting cesium accumulation that have been examined include the addition of stable cesium and chelating agents, changes in temperature, and differences in body weight. No effect on CFs of the addition of stable cesium or of chelating agents was found (Hiyama and Shimizu, 1964). However, the rate of accumulation of cesium by a number of species was found to decrease with increased body size and to increase with increased temperature of the water (Morgan, 1964; Nakahara _et_ _al._, 1977).

A comprehensive study of the accumulation of ^{134}Cs from seawater by the plaice and the thornback ray was conducted (Jefferies and Hewett, 1971). For these species, information is available on organ as well as whole body accumulation. Every organ of the plaice accumulated ^{134}Cs at a faster rate than that of the ray.

Elimination Rates

Elimination of cesium in whole fish and fish muscle is relatively slow (Table 19). In plaice and the thornback ray, kinetics of elimination of cesium were evaluated from experiments that followed both the accumulation and loss of the radionuclide; the biological half-lives compared well.

Table 18. Laboratory-derived concentration factors for cesium in Chordata - Pisces.

Organism	Body part	Exposure d	CFs	Comments
Blennius sp. (blenny)[a]	Flesh	100-200	36,15	--
Blennius sp.[b]	Whole	100-200	15-35	--
Blennius sp.[b]	Flesh	100-200	15-35	--
Micropogon undulatus[c] (Atlantic croaker)	Muscle	29	4.5	(Nonequilibrium)
Paralichthys dentatus (flounder)[c]	Whole	91	9	--
Acanthogobius flavimanus (goby)[d]	Muscle	>30	25	--
Pleuronectes platessa (plaice)[e]	Muscle	800	20.2	--
P. platessa[e]	Whole	800	10.6	--
Raja clavata (thornback ray)[e]	Muscle	800	2.3	--
R. clavata[e]	Whole	800	3.4	--
Clupea harengus (herring)[f]	Whole	28	9.2	--
Pollachius virens (coalfish)[f]	Whole	28	4.0	--
P. pollachius[f]	Whole	28	3.5	--
Mugil chelo (grey mullet)[f]	Whole	28	2.7	--
Gadus morhua (cod)[f]	Whole	28	2.7	--
Trisopterus luscus (whiting)[f]	Whole	28	2.1	--
Anguilla anguilla (eel)[f]	Whole	28	1.6	--
Scophthalamus maximus (turbot)[f]	Whole	28	2.8	--
S. rhombus[f]	Whole	28	2.6	--
Limanda limanda (dab)[f]	Whole	28	2.5	--
Solea solea (sole)[f]	Whole	28	2.5	--
P. platessa[f]	Whole	28	2.1	--
R. clavata[f]	Whole	28	0.5	--

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[a] Ancellin and Vilquin (1968).

[b] Avargues *et al*. (1968).

[c] Baptist and Price (1962).

[d] Hiyama and Shimizu (1964).

[e] Jefferies and Hewett (1971).

[f] Morgan (1964).

Table 19. Biological half-life (days) of cesium in Chordata - Pisces.

Organism	Body part	Pool A[a]	Pool B[a]	Comments
Paralichthys dentatus[b] (flounder)	Whole	5.3(34)	36.9(66)	--
Micropogon undulatus[b] (Atlantic croaker)	Muscle	34.8(35)	94.7(61)	--
Blennius pholis (blenny)[c]	Whole	20-30(12)	203 ± 18(88)	--
Mugil chelo (mullet)[c]	Whole	20-30(25)	154 ± 24(75)	--
Pleuronectes platessa (plaice)[d]	Whole	57.9(100)	--	--
P. platessa[d]	Muscle	139.0(100)	--	--
Raja clavata (thornback ray)[d]	Whole	68.8(100)	--	--
R. clavata[d]	Muscle	126.4(100)	--	--
P. platessa[e]	Whole	64.7(100)	--	Uptake from water
P. platessa[e]	Muscle	120.3(100)	--	Uptake from water
R. clavata[e]	Whole	179.7(100)	--	--
R. clavata[e]	Muscle	189.3(100)	--	--
Evynnis japonica (sea bream)[f]	Whole	75-95(100)	--	--
Helicolenus hilgendorf[f] (scorpionfish)	Whole	75-95(100)	--	--

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[a] Number in parentheses is the percent in the pool.

[b] Baptist and Price (1962).

[c] Fraizier and Vilquin (1971).

[d] Hewett and Jefferies (1978).

[e] Jefferies and Hewett (1971).

[f] Suzuki *et al*. (1978).

STRONTIUM

PHYSICOCHEMICAL FORM

Strontium has physicochemical properties similar to calcium and, like calcium, appears mainly in ionic form in water. In seawater, calcium serves as a nonisotopic carrier for strontium. The concentration of strontium in surface seawater is 7.4 mg/kg and that of calcium is 417.6 mg/kg (Quinby-Hunt and Turekian, 1983). Neither strontium nor calcium is strongly sorbed by particulate material. The mean K_d recommended for use in models of coastal waters is 1000 and that for the pelagic waters sea is 200; the ranges are 100 to 5000 and 2 to 500, respectively (IAEA, 1985). Because of the low K_d of strontium in marine ecosystems, most of the strontium is found in the water column.

PRIMARY PRODUCERS

Concentration Factors

The CF values of strontium reported for microalgae ranged from 4 to 1600 (Table 20). A comparably wide range was found in field populations also (Fig. 9). Experiments performed to evaluate factors affecting the uptake of strontium by phytoplankton showed that the uptake of strontium was proportional to the concentration of strontium in the medium (Corcoran and Kimball, 1963). Furthermore, concentrations up to ten times the normal concentrations of strontium did not seem to affect growth or strontium accumulation. For macroalgae, the upper extent of the range of values reported was lower than that for microalgae for both field- and laboratory-derived data (Fig. 9).

Elimination Rates

No laboratory-derived data on elimination rates of strontium in primary producers were found.

Table 20. Laboratory-derived concentration factors (CFs) for strontium in primary producers.

Organism	Exposure, d	CFs	Comments
	Microalgae		
Nitzschia closterium[a]	--	17	--
Phytoplankton[b]	--	9	--
Chlamydomonas minima[c]	--	4	--
Carteria sp.[d]	24	561	--
Carteria sp.[d]	24	1600	Rapidly growing
	Macroalgae		
Ulva lactuca (green alga)[e]	10	0.3	Extracted from dead plants
Monostroma sp. (green alga)[f]	7	6.7	7 and 70 mg Sr/L
Sargassum thunbergii (brown alga)[f]	7	6.5	7 and 70 mg Sr/L
Gracilaria confervoides (red alga)[f]	7	5.3	7 and 70 mg Sr/L
Fucus serratus (brown alga)[g]	8	40	--
Ulva rigida (green alga)[g]	8	2	--
U. lactuca (green alga)[g]	8	1	--
Dictyota fasciola (brown alga)[g]	--	18	--
Padina pavonia (brown algae)[g]	--	19	--
Cystoseira barbata (brown alga)[g]	--	40	--
Corallina rubens (red alga)[g]	--	4	--
Ceramium rubrum (red alga)[g]	--	1	--
Polysiphonia elongata (red alga)[g]	--	1	--
Phyllophora nervosa (red alga)[g]	--	8	--
Green alga[h]	26	0.8 + 0.0	--
Green alga[h]	26	1.0 ± 0.0	--
Brown alga[h]	26	42.1 ± 2.0	--
Brown alga[h]	26	25.3 ± 3.4	--
Brown alga[h]	26	6.4 ± 0.2	--
Red alga[h]	26	1.4 ± 0.0	--
Red alga[h]	26	3.8 ± 0.2	--
Red alga[h]	26	1.3 ± 0.0	--
Red alga[h]	26	2.2 ± 0.4	--
Red alga[h]	26	2.3 ± 0.0	--

Table 20. (Continued).

Organism	Exposure, d	CFs	Comments
Fucus serratus (brown alga)[i]	--	40	--
F. serratus[i]	--	30	In dark
F. vesiculosus[i]	--	23	--
F. vesiculosus[i]	--	35	New growth
Ascophyllum nodosum (brown alga)[i]	--	22	--
Laminaria digitata (brown alga)[i]	--	14	--
Chrondrus crispus (red alga)[i]	--	1.7	--
Gigartina stellata[i]	--	2.2	--
Ulva lactuca (green alga)[i]	--	1.2	--

[a] Boroughs *et al*. (1957).

[b] Martin (1958), cited from Jackson *et al*. (1983).

[c] Polikarpov (1964).

[d] Rice (1956).

[e] Hampson (1967), cited from Jackson *et al*. (1983).

[f] Hiyama and Shimizu (1964).

[g] Polikarpov (1966).

[h] Ryndina (1972), cited from Jackson *et al*. (1983).

[i] Spooner (1949).

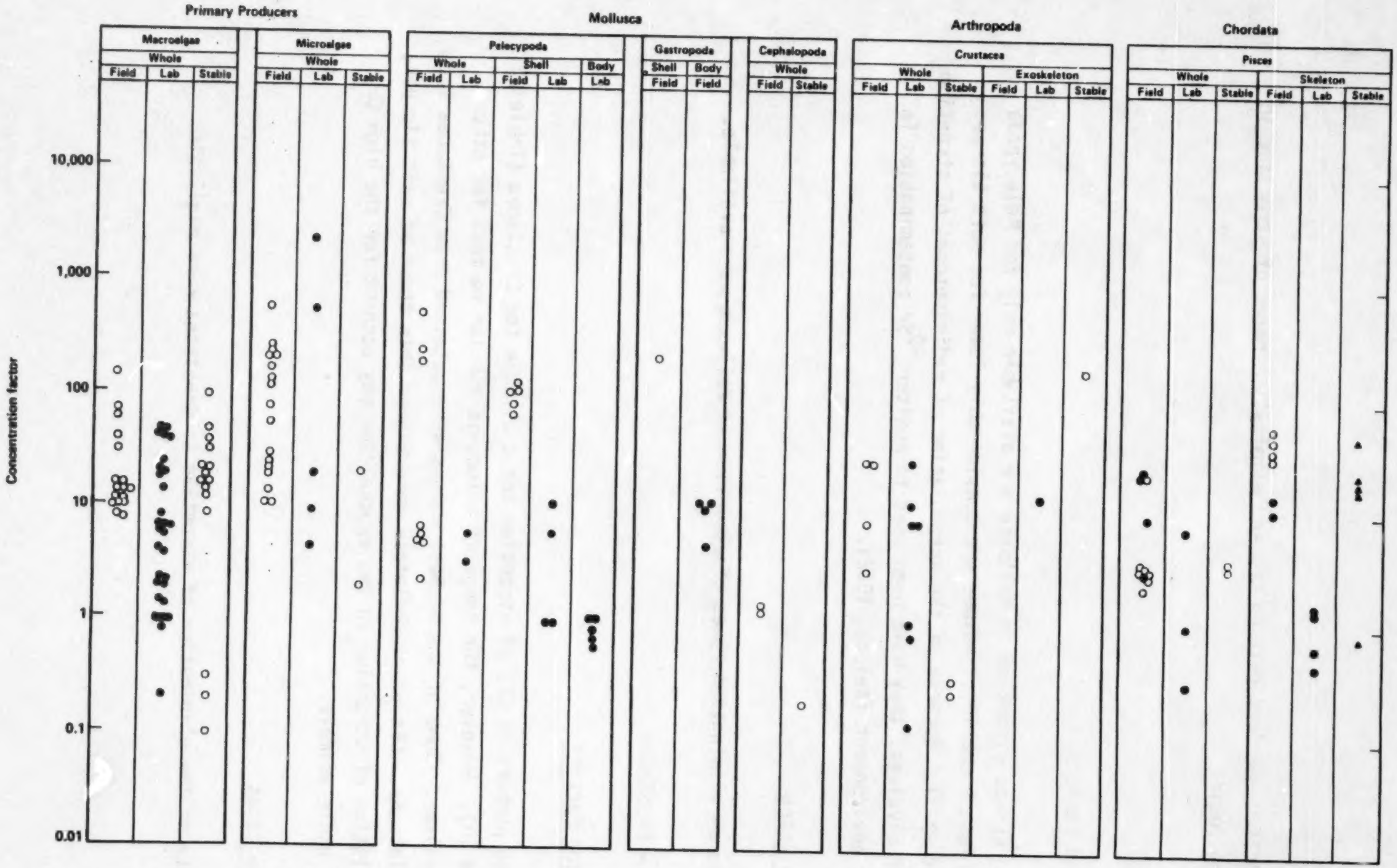

Figure 9. Concentration factors (CFs) for strontium in marine biota: laboratory-derived CFs from this report (•); field-derived CFs from Jackson et al. (1983) (o) or Noshkin (1985) (•); stable-element-derived CFs from Polikarpov (1966) (o) or Pentreath (1977) (▲).

ANNELIDA

No laboratory-derived data on CFs and elimination rates of strontium in Annelida were found.

MOLLUSCA

Concentration Factors

Data on CFs of strontium in Mollusca are available only for Pelecypoda (Table 21, Figs. 9 and 10). Values are considerably lower for soft tissues than for the shell. Because of the accumulation of radioisotopes of strontium in shells of bivalves, they have been used to monitor ^{90}Sr contamination in the aquatic environment (Nelson, 1962).

Elimination Rates

No data on elimination rates of strontium in Mollusca were available.

ARTHROPODA - CRUSTACEA

Concentration Factors

Limited numbers of CFs of strontium are available for Crustacea (Table 22, Figs. 9 and 10). However, the range of values is similar to that for other marine organisms. Some of the highest values were obtained from Crustacea from field populations. CFs of exoskeletons were higher than those of soft tissues, and accumulation of strontium in the exoskeleton may account for the high CF values for whole animals.

Elimination Rates

No data on the elimination of strontium in Crustacea were available.

Table 21. Laboratory-derived concentration factors (CFs) for strontium in Mollusca - Pelecypoda.

Organism	Body part	Exposure d	CFs	Comments
Mytilus galloprovincialis[a] (mussel)	Whole	5	3.6	--
Crassostrea sp. (oyster)[b]	Body	--	1	--
Mercenaria mercenaria (clam)[c]	Shell	--	10	Nonequilibrium
M. mercenaria[c]	Body	--	0.9	--
Meretrix meretrix (clam)[d]	Muscle	20	>0.7	--
Venerupis philippinarum (clam)[d]	Muscle	20	>0.4	--
V. philippinarum[d]	Body	20	0.8	7 mg Sr/L
V. philippinarum[d]	Shell	20	1.5	7 mg Sr/L
V. philippinarum[d]	Body	18	0.5	70 mg Sr/L
V. philippinarum[d]	Shell	18	1.6	70 mg Sr/L
Mytilus edulis (mussel)[e]	Body	64	0.7	--
M. edulis[e]	Shell	64	6	--
M. edulis[e]	Whole	64	6	--

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[a] Argiero *et al*. (1966).

[b] Boroughs *et al*. (1957).

[c] Chipman (1959).

[d] Hiyama and Shimizu (1964).

[e] Polikarpov (1961).

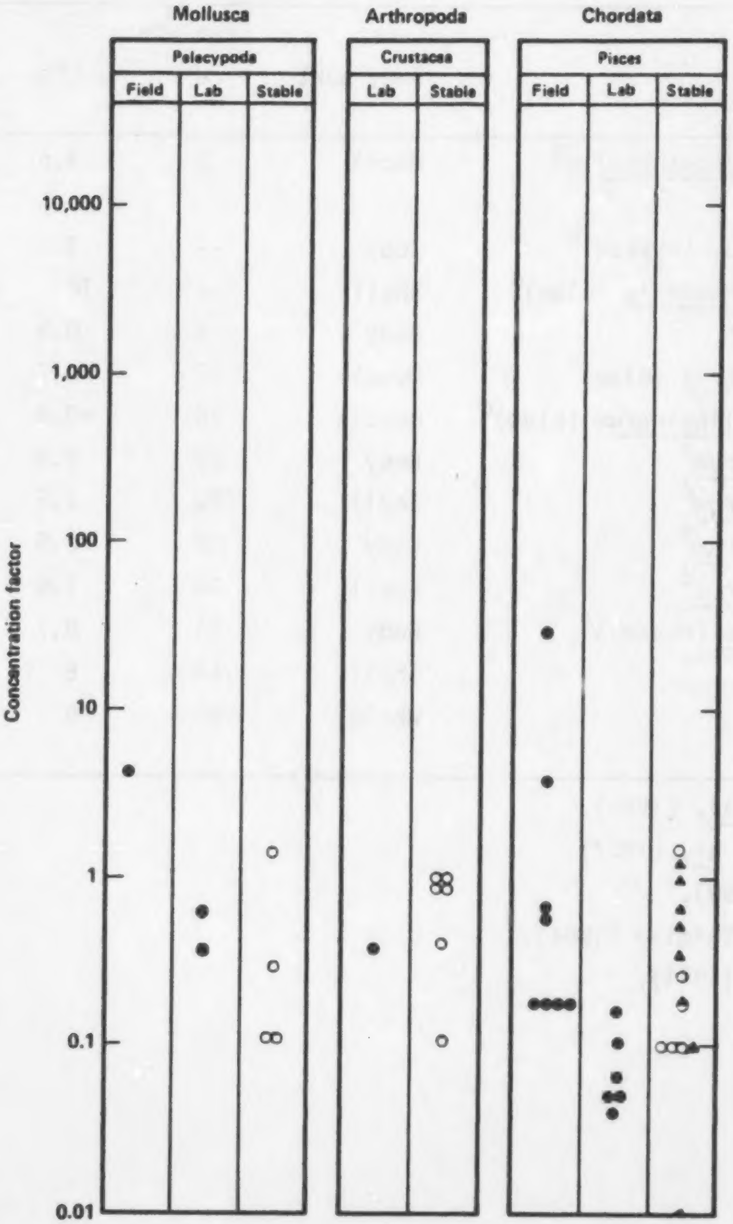

Figure 10. Whole-body concentration factors (CFs) for strontium in muscle tissue of marine biota: laboratory-derived CFs from this report (●) field-derived CFs from Noshkin (1985) (●); stable-element-derived CFs from Polikarpov (1966) (o) or Pentreath (1977) (▲).

Table 22. Laboratory-derived concentration factors (CFs) for strontium in Arthropoda - Crustacea.

Organism	Body part	Exposure, d	CFs	Comments
Artemia salina (brine shrimp)[a]	Whole	1	0.7	Nauplii
A. salina[a]	Whole	3.8	0.2	--
Tigropus californicus[a]	Whole	--	1	--
Leander sp. (shrimp)[b]	Muscle	9	0.2	--
Leander sp.[b]	Exoskeleton	9	15	--
L. squilla[c]	Whole	64	8	Nonequilibrium
Krill[d]	Whole	4-6	8.0 ± 0.6	Site 1
Krill[d]	Whole	4-6	12.1 ± 0.9	Site 2
Krill[d]	Whole	4-6	29 ± 0.9	Site 3

[a] Boroughs *et al*. (1958).

[b] Hiyama and Shimizu (1964).

[c] Polikarpov (1966).

[d] Tolkach and Gromov (1976).

CHORDATA - PISCES

Concentration Factors

Laboratory-derived CFs of strontium have been obtained for both bony and cartilagenous fishes (Table 23). Examination of the experimental data on accumulation of strontium shows that almost all the experiments were too short in duration for steady-state conditions of uptake and loss to have occurred. Absence of equilibrium conditions is indicated also because the field-derived CFs were larger than the laboratory-derived CFs (Figs. 9 and 10).

The effect of differing calcium and strontium concentrations on the occurrence of the radioisotopes of these elements in tissues as well as the relative role of the food and water pathway in accumulation of strontium have been examined. However, the interpretation of the results from studies of both of these factors is controversial. Because the results of these investigations have been reviewed recently (Pentreath, 1981), a discussion of the data will not be included here.

Elimination Rates

The metabolism of strontium in the Atlantic croaker *Micropogon undulatus* was investigated by Baptist *et al*. (1970). The loss was biphasic and the half-lives were 1.25 d and 138 d for the short- and long-lived components, respectively. The short-lived component was 21% and the long-lived was 79% of the total activity. Analysis of the rates of loss from tissues indicated that the long-lived component represented loss from bones and scales.

COBALT

PHYSICOCHEMICAL FORM

Cobalt is commonly present in more than one chemical form in seawater. It can be present in ionic form or associated with dissolved organic material. Cobalt may also be present in low concentration in the form of cyanocobalamin (vitamin B 12), which is required by many aquatic organisms but synthesized by only a few. The concentration of cobalt in surface waters is 7 ng/kg and in deep waters is 2 ng/kg (Quinby-Hunt and Turekian, 1983). These authors state

Table 23. Laboratory-derived concentration factors (CFs) for strontium in Chordata - Pisces.

Organism	Body part	CFs	Comments
Tilapia mossambica[a]	Whole	0.3	Euryhaline
Mugil cephalus (mullet)[b]	Whole	5	Young
Fundulus heteroclitus[b] (mummichog)	Muscle	0.1	--
Rudarius ercodes[c]	Muscle	0.03	--
R. ercodes[c]	Vertebra	0.5	Nonequilibrium
Pterogobius elapoides[c]	Muscle	0.04	--
P. elapoides[c]	Vertebra	1.4	Nonequilibrium
Acanthogobius flavimanus (goby)[c]	Muscle	0.04	--
A. flavimanus[c]	Vertebra	0.7	Nonequilibrium
Trachurus japonicus[c]	Muscle	0.06	--
T. japonicus[c]	Vertebra	1.5	Nonequilibrium
Pleuronectes platessa (plaice)[d]	Whole	1.0	--
P. platessa[d]	Flesh	0.15	--

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[a] Boroughs *et al.* (1956).

[b] Chipman (1959).

[c] Hiyama and Shimizu (1964).

[d] Templeton (1959), cited from Jackson *et al.* (1983).

that cobalt is maximum in concentration in surface waters and, with depth, is positively correlated with the labile nutrients and negatively correlated with dissolved oxygen.

The K_d for cobalt is higher than that for cesium and strontium. The mean K_d recommended for use in models of coastal waters is 100,000 and that for pelagic areas is 3,000,000; the ranges are 20,000 to 500,000 and 50,000 to 5,000,000, respectively. Because of its high affinity for particulate material, cobalt is found primarily in the particulate fraction of the water column.

PRIMARY PRODUCERS

Concentration Factors

Although the data available on CFs of cobalt determined under field and laboratory conditions in microalgae are limited, CFs have been determined for many different macroalgae (Table 24, Fig. 11). The range of CFs for macroalgae is similar for stable-element- and radionuclide-derived values. These results indicate that steady-state conditions of uptake and loss of cobalt were probably reached in the laboratory experiments.

The marine alga Dunaliella bioculata was found to concentrate ^{60}Co rapidly, and the CF determined was considerably lower in the presence of increased concentrations of stable cobalt (Kirchmann et al., 1977). The accumulation of ^{60}Co by Ulva sp. is reported to be dependent on light; the CF was 2.5 times higher in algae grown in the light than in the dark. These results indicate that accumulation of cobalt may be an active rather than a passive process.

Elimination Rates

Few data are available on the biological half-life of cobalt in primary producers. The biological half-life of cobalt in Ulva pertusa was determined to be 10 d (Nakahara et al., 1975). The loss of ^{60}Co from Halimeda incrassata was found to be fit best by a one-compartment model; the half-life was 9.4 d (Spies et al., 1981). Mattsson et al. (1980) reported a biological half-life of 60 ± 15 d for Fucus vesiculosus that was collected from waters around the Barseback Nuclear Plant.

Table 24. Laboratory-derived concentration factors (CFs) for cobalt in primary producers.

Organism	Body part	Exposure, d	CFs	Comments
Microalgae				
Dunaliella bioculata[a]	Whole	27	100	--
Phytoplankton[b]	Whole	--	326	--
Macroalgae				
Porphyra sp. (red alga)[a]	Whole	19	314	--
Acetabularia mediterranea[a] (green algae)	Whole	2	187	--
A. mediterranea[a]	Whole	21	410	--
A. mediterranea[a]	Whole	25	228	--
Ulva lactuca (green algae)[a]	Whole	19	612	--
U. pertusa[c]	Whole	22	380	August
U. pertusa[c]	Whole	22	>17	April
Sargassum thunbergii (brown alga)[c]	Whole	22	420	--
A. mediterranea[d]	Whole	7	200-400	--
A. mediterranea[d]	Chloroplasts	7	18-25	--
U. pertusa[e]	Whole	20	439	--
Laminaria japonica (brown alga)[e]	Whole	20	138	--
Eisenia bicyclis (brown alga)[e]	Whole	20	34	--
Undaria pinnatifida (brown alga)[e]	Whole	20	120	--
Hizikia fusiforme (brown alga)[e]	Whole	20	127	--
Sargassum thunbergii (brown alga)[e]	Whole	20	2574	--
Chondrus ocellatus (red alga)[e]	Whole	20	833	--
Ahnfeltia paradoxa (red alga)[e]	Whole	20	290	--

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[a] Bonotto et al. (1978).

[b] Martin (1958), cited from Jackson et al. (1983).

[c] Hiyama and Khan (1964).

[d] Kirchmann et al. (1977).

[e] Nakahara et al. (1975).

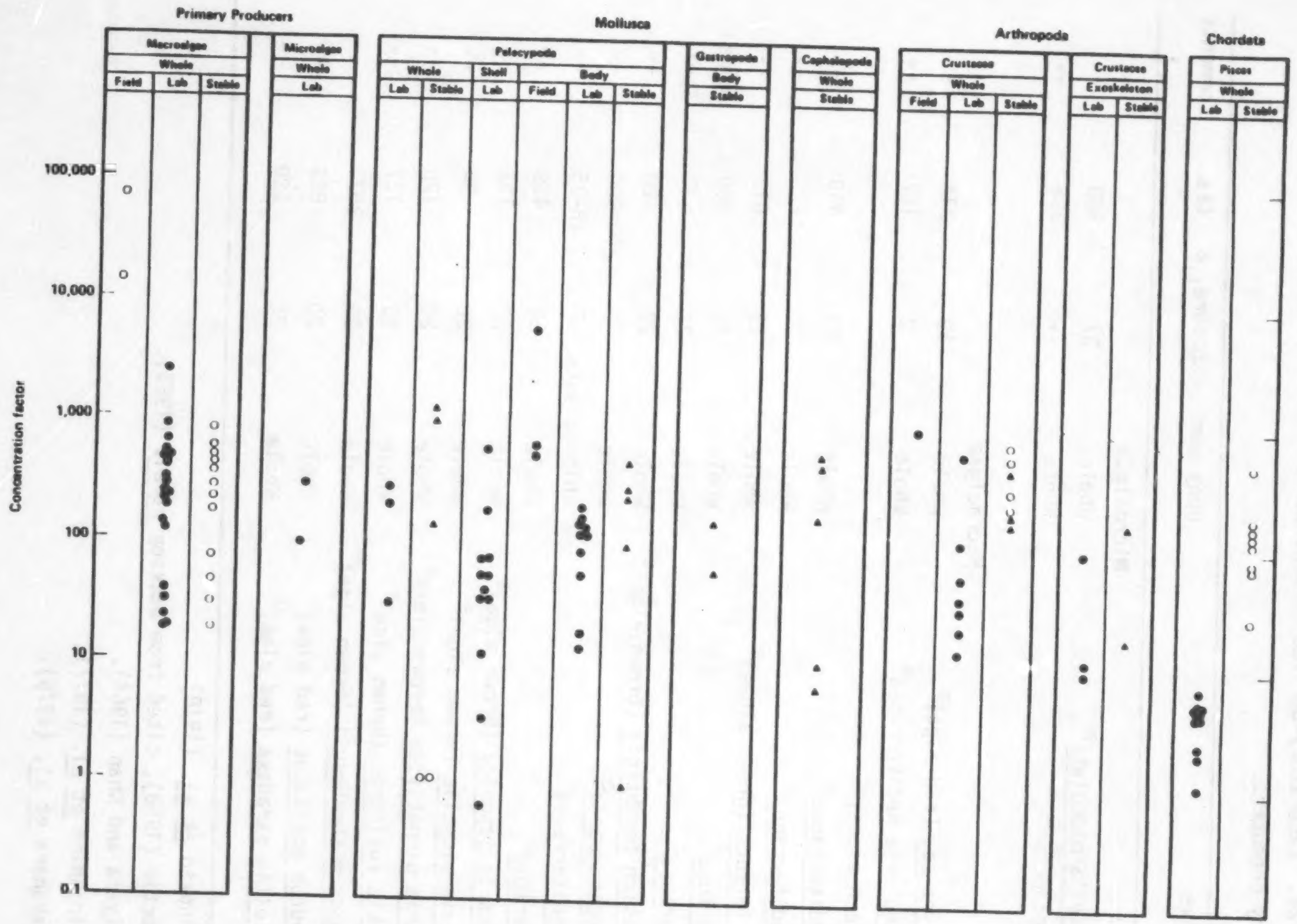

Figure 11. Concentration factors (CFs) for cobalt in marine biota: laboratory-derived CFs from this report (●); field-derived CFs from Jackson et al. (1983) (o) or Noshkin (1985) (●); stable-element-derived CFs from Polikarpov (1966) (o), Shimizu et al. (1970) (▲).

ANNELIDA - POLYCHAETA

Concentration Factors

CF values of cobalt have been determined for only a few polychaete worms. For Arenicola marina, CFs of 10 for the coelomic fluid, 1000 for the blood, and 25 for the digestive tract were determined (Triquet, 1973). For whole A. marina, a CF of 335 was obtained (Amiard-Triquet, 1975). For Neanthes diversicolor, uptake of cobalt from water, food and water, and sediment was investigated (Ueda et al., 1977). The CFs obtained from worms exposed to radioactive cobalt in the water was 6 ± 1, in the food and water was 7, and in the sediment was 0.045 and 0.055. Young (1982) investigated the accumulation by Neanthes virens of ^{60}Co released into seawater from the corrosion of neutron-activated stainless steel. The average CF from water during months 6 to 13 of the exposure was 343 ± 123 and from sediment was 2.25 ± 0.36.

Elimination Rates

The loss of ^{60}Co from Nereis japonica was followed for 24 d (Ueda et al., 1977). There was a rapid loss of ^{60}Co during the first 2 to 3 d and then the rate of loss was slower. The half-life obtained for the slower compartment was 37 d.

MOLLUSCA

Concentration Factors

CF values of cobalt in Mollusca are presented in Table 25 and Figs. 11 and 12. The highest values were obtained in the experiments of longest duration. Comparison of the field- and laboratory-derived data shows that the range of values for the body was different (Fig. 10). These data indicate absence of steady-state conditions for most, if not all, populations exposed under laboratory conditions.

Investigations have been made of the importance of food and water in the uptake of cobalt by Mollusca. Nakahara et al. (1976) showed that the absorption of ^{60}Co by some Mollusca depended on the species of algae on which they were fed; the percent absorbed varied from 26 to 47. Amiard (1978)

Table 25. Laboratory-derived concentration factors (CFs) for cobalt in Mollusca.

Organism	Body part	Exposure d	CFs	Comments
	Pelecypoda			
Scrobicularia plana (clam)[a]	Body	35	32	--
S. plana[a]	Shell	35	76	--
Macoma balthica (clam)[a]	Body	35	22	--
M. balthica[a]	Shell	35	53	--
Mytilus edulis (mussel)[b]	Whole	26	30	--
Crassostrea gigas (oyster)[c]	Whole	48	300	--
C. gigas[c]	Body	48	51	--
C. gigas[c]	Muscle	48	41	--
C. gigas[c]	Shell	48	610	--
Mya arenaria (clam)[d]	Whole	179	220	--
M. arenaria[d]	Body	179	82	--
M. arenaria[d]	Muscle	179	100	--
Phaphia philippinarum (clam)[e]	Shell	10	35	No carrier
P. philippinarum[e]	Viscera	10	10	No carrier
P. philippinarum[e]	Shell	10	3	Carrier added
P. philippinarum[e]	Viscera	10	2	Carrier added
Venerupis philippinarum (clam)[f]	Viscera	22	9.2	--
V. philippinarum[f]	Muscle	22	>7	--
V. philippinarum[f]	Shell	22	36	--
Mytilisepta virgatus[g] (mussel)	Body	40	1.4	Trisglycinato complex of Co
M. virgatus[g]	Body	40	13	Ionic Co
M. virgatus[g]	Shell	40	0.7	Trisglycinato complex of Co
M. virgatus[g]	Shell	40	11	Ionic Co
M. virgatus[g]	Muscle	40	0.8	Trisglycinato complex of Co
M. virgatus[g]	Muscle	40	8.5	Ionic Co
Mytilus edulis (mussel)[h]	Body	15-35	140	$CoCl_2$,200 ppm
M. edulis[h]	Shell	15-35	190	$CoCl_2$,200 ppm

Table 25. (Continued).

Organism	Body part	Exposure d	CFs	Comments
M. edulis[i]	Body	60	135 ± 40	Nonequilibrium
M. edulis[i]	Shell	60	40 ± 18	Nonequilibrium
M. edulis[i]	Body	60	155 ± 30	Nonequilibrium
M. edulis[i]	Shell	60	75 ± 30	Nonequilibrium
M. edulis[i]	Body	60	120 ± 20	Nonequilibrium
M. edulis[i]	Shell	60	52 ± 15	Nonequilibrium
Macoma inquinata[j]	Whole	390	244 ± 95	From water
M. inquinata[j]	Whole	390	0.48 ± 0.1	From sediment
	Cephalopoda			
Octopus or squid[k]	Muscle	30	15	--

[a] Amiard-Triquet (1975).
[b] Bonotto *et al*. (1981).
[c] Cranmore and Harrison (1975).
[d] Harrison (1973).
[e] Hiyama (1962).
[f] Hiyama and Khan (1964).
[g] Nishiwaki *et al*. (1981).
[h] Shimizu *et al*. (1970).
[i] van Weers (1973).
[j] Young (1982).
[k] Nakahara *et al*. (1979a).

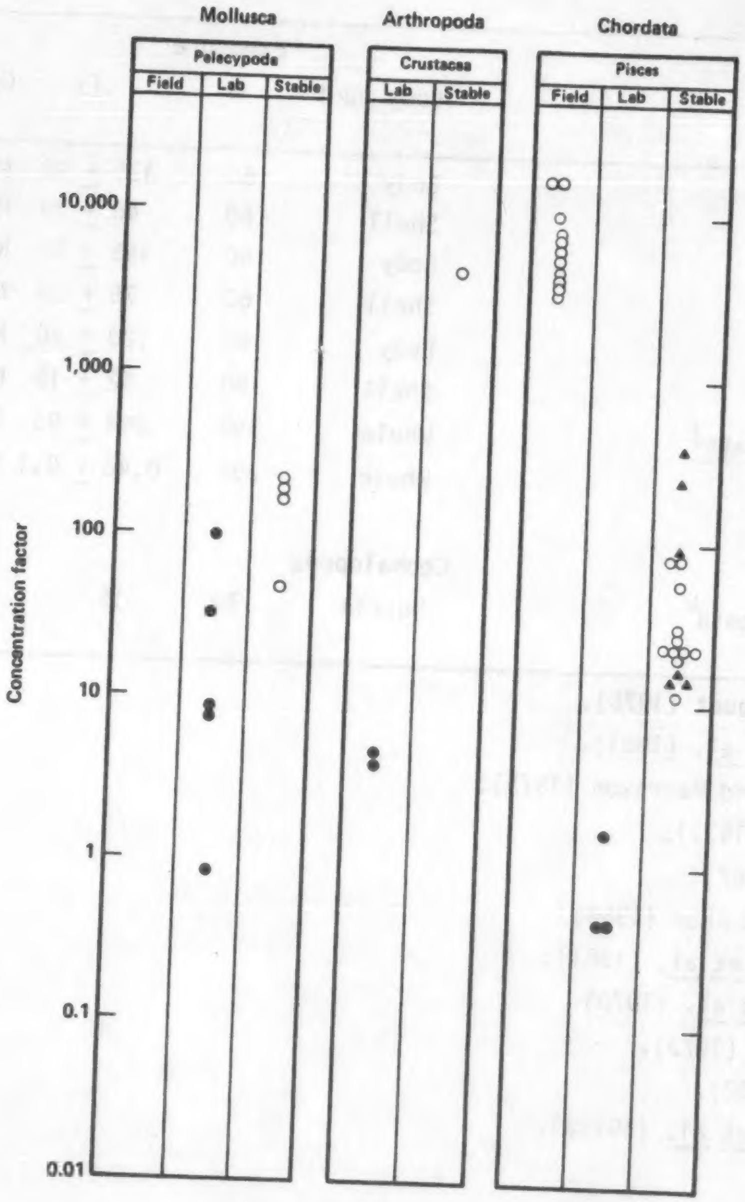

Figure 12. Concentration factors for cobalt in muscle tissue of marine biota: laboratory-derived CFs from this report (●); field-derived CFs from Jackson *et al*. (1983) (o); stable-element-derived CFs from Polikarpov (1966) (o) or Pentreath (1977) (▲).

reported that the CFs obtained from short-term exposure to cobalt in the water were 300 to 400 times greater than those from food. When accumulation had occurred over a 2-month period, CFs from the water pathway were 7.6 times that from the food pathway.

The accumulation of ionic cobalt and cobalamin by the abalone Haliotis discus was compared (Ueda et al., 1981). They reported that the distribution of cobalt in the liver was different for the two forms of cobalt.

Elimination Rates

Metabolism of cobalt has been investigated in both clams and oysters (Table 26). Generally, elimination was several months in duration in the long-lived compartment. Pentreath (1973a) investigated the uptake of cobalt in various tissues of Mytilus edulis. When the radionuclide was administered in the water, half-lives ranged from 4.7 d in the foot to 17.7 d in the adductor muscle. He concluded from his analysis of stable-element data that accumulation of radionuclides from water was minor relative to that from the food.

The accumulation and loss of ^{60}Co by the octopus Octopus vulgaris was followed by Nakahara et al. (1981). The distribution of the ^{60}Co in octopuses that had accumulated the radionuclide from the food differed from that in octopuses that had accumulated it from the water. The biological half-life of ^{60}Co calculated from the long component of the excretion curve of whole body radioactivity was approximately 200 d for the organisms reared in labeled seawater and was 300 d for those administered labeled food.

ARTHROPODA - CRUSTACEA

Concentration Factors

CF values of cobalt for crustaceans are presented in Table 27. It is not known whether the considerable variability shown is due to differences in species or the absence of equilibrium conditions. Most of the cobalt was present in the exoskeleton and would be lost from the animal upon molting.

Amiard and Amiard-Triquet (1977) followed the uptake of cobalt from food and seawater in the crab Carcinus maenas. The CF resulting from cobalt in the water was 5.8 times that from food.

Table 26. Biological half-life (days) of cobalt in Mollusca - Pelecypoda.

Organism	Body part	Pool A[a]	Pool B[a]
Scrobicularia plana[b] (clam)	Whole	2-4(--)	30-57(--)
Crassostrea gigas[c] (oyster)	Whole	220(--)	40(--)
C. gigas[c]	Body	130(--)	7(--)
C. gigas[c]	Muscle	300(--)	12(--)
C. gigas[c]	Shell	100(--)	35(--)
Mya arenaria (clam)[d]	Whole	120(100)	--
M. arenaria[d]	Body	240(100)	--
M. arenaria[d]	Muscle	180(100)	--
Crassostrea virginica[e] (oyster)	Whole	35(100)	--

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[a] Number in parentheses is the percent of total activity in the pool.

[b] Amiard-Triquet and Amiard (1976a, b).

[c] Cranmore and Harrison (1975).

[d] Harrison (1973).

[e] Hess et al. (1977).

Table 27. Laboratory-derived concentration factors (CFs) for cobalt in Arthropoda - Crustacea.

Organism	Body part	Exposure, d	CFs	Comments
Crangon vulgaris[a] (shrimp)	Whole	12	37	--
C. vulgaris[a]	Exoskeleton	12	100	--
Carcinus maenas[a] (crab)	Whole	7	30	--
Leander pacificus[b] (shrimp)	Whole	19	20	No carrier
L. pacificus[b]	Whole	19	5	Carrier added
L. pacificus[c]	Muscle	15-35	5	No carrier
L. pacificus[c]	Exoskeleton	15-35	18	No carrier
L. pacificus[c]	Muscle	15-35	4	$CoCl_2$, 200 ppm
L. pacificus[c]	Exoskeleton	15-35	14	$CoCl_2$, 200 ppm
Clibanarius virescens[c] (hermit crab)	Whole	15-35	520	$CoCl_2$, 200 ppm
C. virescens[c]	Whole	15-35	57	$CoCl_2$, 200 ppm
Crangon crangon[d]	Whole	30	13	Water

[a] Bonotto *et al*. (1981).

[b] Hiyama (1962).

[c] Shimizu *et al*. (1970).

[d] van Weers (1975).

Elimination Rates

Little information is available on the biological half-life of cobalt in Crustacea. Amiard-Triquet and Amiard (1976b) found that the rate of loss of ^{60}Co from the fast compartment was related to the frequency of feeding. No data on half-lives were given. When the shrimp *Crangon crangon* was fed ^{60}Co-labeled mussel flesh and then the loss of activity followed, two components of loss were identified (van Weers, 1975). The short-lived component had a mean biological half-life of 1.2 d and accounted for about 80% of the initial activity. The long-lived component had a half-life of about 10 d and represented about 20% of the activity.

CHORDATA - PISCES

Concentration Factors

Data on CFs of cobalt in marine fishes are limited (Table 28). Values are considerably lower than those of Mollusca and Crustacea. Comparison of field-derived stable-element and laboratory-derived radionuclide CF values shows that the range of the stable-element values is more than an order of magnitude higher than that obtained under laboratory conditions. The accumulation of cobalt from food and water was compared in the yellowtail (*Seriola quinqueradiata*) (Nakahara *et al.*, 1979b; Suzuki *et al.*, 1979). After the fish were exposed for a 7-d period, the percentages of ^{60}Co in tissues were different for the two pathways, but the significance of the pattern of the differences was not apparent.

The accumulation of ^{58}Co by the thornback ray was followed for 84 d (Pentreath, 1973b). Data on organ CFs show a high value of 2.2 in the gills and a low value of 0.3 in the muscle. This investigator concluded that intake from water played only a relatively minor role in the accumulation of cobalt by the ray.

Elimination Rates

The biological half-life of cobalt has been determined for a number of species (Table 29). The elimination of cobalt was followed in the Atlantic croaker *Micropogon undulatus* after intraperitoneal injections (Baptist *et al.*,

Table 28. Laboratory-derived concentration factors (CFs) for cobalt in Chordata - Pisces.

Organism	Body part	Exposure, d	CFs	Comments
Girella punctata[a]	Whole	22	>5	No carrier
G. punctata[a]	Whole	22	>2	Carrier added
Chasmichthys gulosus[b]	Whole	22	4.5	July, small size
C. gulosus[b]	Whole	22	5.2	Oct., small size
C. gulosus[b]	Whole	22	2.5	Medium size
Brevootia tyrannus[c] (post-larvae menhaden)	Whole	16	7.1	Nonequilibrium
Sebastes nivosus[c] (rock fish)	Whole	20	4.2	Nonequilibrium
Evynnis japonica[c] (sea bream)	Whole	62	4.8	--
E. japonica[c]	Muscle	62	0.5	--
Seriola quinqueradiata[c] (yellowtail)	Whole	131	1.2	--
S. quinqueradiata[c]	Muscle	131	0.3	--
Paralichthys olivaceus[c] (flounder)	Whole	120	5.5	--
P. olivaceus[c]	Muscle	20	1.5	--

[a] Hiyama (1962).

[b] Hiyama and Khan (1964).

[c] Nakahara *et al*. (1979b).

Table 29. Biological half-life (days) of cobalt in Chordata - Pisces.

Organism	Body Part	Pool A[a]	Pool B[a]	Comments
Micropogon undulatus[b] (Atlantic croaker)	Whole	31(100)	--	Intraperitoneal injection
Blennius pholis[c] (blenny)	Whole	203±18(88)	20-30(12)	Loss after uptake from water
Mugil chelo[c] (grey mullet)	Whole	154±24(75)	20-30(25)	Loss after uptake from water
Evynnis japonica[d] (sea bream)	Whole	28.9(--)	--	Loss after uptake from water
E. japonica[d]	Muscle	38.5(--)	--	Loss after uptake from water
Seriola quinqueradiata[d] (yellowtail)	Whole	23.9(--)	--	Loss after uptake from water
S. quinqueradiata[d]	Muscle	53.3(--)	--	Loss after uptake from water
Paralichthys olivaceus[d] (flounder)	Whole	49.5(--)	--	Loss after uptake from water
P. olivaceus[d]	Muscle	63.0(--)	--	Loss after uptake from water
Pleuronectes platessa[e] (plaice)	Whole	65(100)	--	Accumulation from water
P. platessa[e]	Muscle	120(100)	--	Accumulation from water
Raja clavata[e] (thornback ray)	Whole	180(100)	--	Accumulation from water
R. clavata[e]	Muscle	189(100)	--	Accumulation from water

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[a] Number in parentheses is the percent of total activity in the pool.

[b] Baptist et al. (1970).

[c] Fraizier and Vilquin (1971).

[d] Nakahara et al. (1979b).

[e] Jefferies and Hewett (1971).

1970) and only one compartment was identified compared to two compartments for the other radionuclides that were examined. These investigators state that more compartments might have been found if loss of the cobalt had been followed for a longer time. The accumulation by the common goby *Acanthogobius flavimanus* of ^{60}Co that had been incorporated into *Nereis japonica* was followed (Kimura and Ichikawa, 1972). A triphasic pattern of loss was found after a single meal of worms had been consumed. The absorption of sediment-bound ^{60}Co was studied after oral administration of encapsulated sediment (Koyanagi *et al*., 1978); loss was found to be biphasic.

APPLICATION OF CONCENTRATION FACTOR AND ELIMINATION RATE DATA

Concentration Factors

CFs for radionuclides in marine organisms are, in general, higher in primary producers than in marine invertebrates, and fish usually have lower CFs than invertebrates (see also reviews by Coughtrey and Thorne, 1983a, b). Examination of the distribution of laboratory-derived CF values for a specific group of organisms shows that the spread of the values may range over several orders of magnitude (Pentreath, 1977, 1981). For a given species, the CF is dependent on whether the analysis was made on the whole organism, on the eviscerated body, on soft tissues only, or on selected organs or tissues. Comparison of laboratory- and field-derived CFs shows that there is better agreement between the data sets for some groups than for others. It is expected that better agreement would occur for organisms or body parts that have short elimination times than for those that have long ones, and for those organisms or body parts where surface adsorption reactions predominate rather than for those where transfer across membranes and uptake by internal tissues is required.

The distribution of radionuclide concentrations in environmental media and the distribution of the resulting CFs calculated from them generally are highly variable and exhibit a skewness. This is readily demonstrated by the plots of CFs in this report. Such CF values are not well represented by a normal distribution, but they are well approximated by a lognormal distribution (i.e., the values of the logarithms of the CFs appear to be normally distributed). Such lognormal distributions for radionuclide concentration data and CF values have been described previously by others, and procedures for the statistical treatment of the data have been given (Gilbert, 1979, 1983).

Because CF values exhibit such a wide range of values, it is difficult to select a single value to use in dose-assessment models. An approach used frequently in the past has been to select a conservative value; however, this practice is currently considered to be a poor procedure except in efforts to protect the public in advance of an actual release of radioactivity. The current approach used by modelers to predict the movement of radionuclides through ecological systems is to stress the use of stochastic models, wherein the actual distribution of data sets is considered and results are specified in a probabilistic nature. This more realistic approach has several important advantages. The most important is that model outputs represent a more realistic assessment of the inherent variability of natural systems, and the regulator is presented with a probability distribution. From this distribution, a desired degree of conservatism can be selected or the dose being calculated can be presented in terms of a probable value and an appropriate statement of uncertainty.

To apply these concepts, however, it is necessary to specify a distribution of values for each of the input parameters used in a model and to propagate uncertainties throughout the model. Therefore, some of the CF data in this report have been examined to specify the distributions of values. Of the radionuclides and groups of organisms discussed in this review, I am considering only the field-derived CFs for plutonium and cesium in fishes and molluscs because they are the only ones with a reasonable body of data.

The two-parameter lognormal distribution is described mathematically by

$$f(x) = [1/(\sigma_y\sqrt{2\pi})]\ \exp[-(\ln x - \mu_y)^2/(2\sigma_y^2)]$$
$$x > 0,\ -\infty > \mu_y > \infty,\ \sigma_y > 0\ ,$$

where μ_y and $\sigma_y{}^2$, the two parameters of the distribution, are the true mean and variance, respectively, of the transformed variate $y = \ln x$ (Gilbert, 1983). The distribution can be described also by the true geometric mean $[\exp(\mu_y)]$ and true geometric standard deviation $[\exp(\sigma_y)]$. Such distributions have several useful properties including the following:

- The product of m independent lognormal variates is also a lognormal variate. This is a very useful property in multiplicative food-chain models.
- The ratio of two lognormal variates (x/y) is also a lognormal variate.

If the several variates are not independent, then in the calculation of the variance, the correlation between the variates must also be considered (Gilbert, 1983). The second point above is important in consideration of the utilization of CF values.

Analyses were performed on the values, cited by Noshkin (1985), of field-derived CFs for plutonium and cesium in fishes and molluscs. The analyses included plotting the values on lognormal probability paper to examine the assumption of lognormality. If a straight line fitted the data reasonably, a lognormal distribution was assumed; all of the CF values analyzed appeared to be reasonably well represented by a lognormal distribution. A probability plot of the CF values for plutonium in fish muscle is shown in Fig. 13. Analyses were performed also to provide data on the median and on the mean, variance, and central percentage interval (plus or minus one standard deviation) with the assumptions that the data were (1) normally distributed and (2) lognormally distributed. The arithmetic mean was always larger than the median or the geometric mean (Table 30).

Examination of the data on the central percentage confidence intervals shows that the values obtained, assuming a normal distribution, are of little value for analysis of uncertainty because negative numbers are obtained (the standard deviation is larger than the mean). It is also clear that the true geometric standard deviations are large. These large true geometric standard deviations could be attributed to many causes. First, the data are not homogeneous; they were obtained by a variety of investigators on a variety of specimens. Second, there may be systematic errors between investigators whose data are represented in the data base. And finally, the biological and chemical systems measured may in fact have very large variability.

In general, the following steps are suggested in the selection of parameters to be used in models.

- Perform a probability plot of the data to determine whether the data are best represented by a normal or lognormal distribution.
- Determine the mean, standard deviation, and confidence intervals for the appropriate distribution.

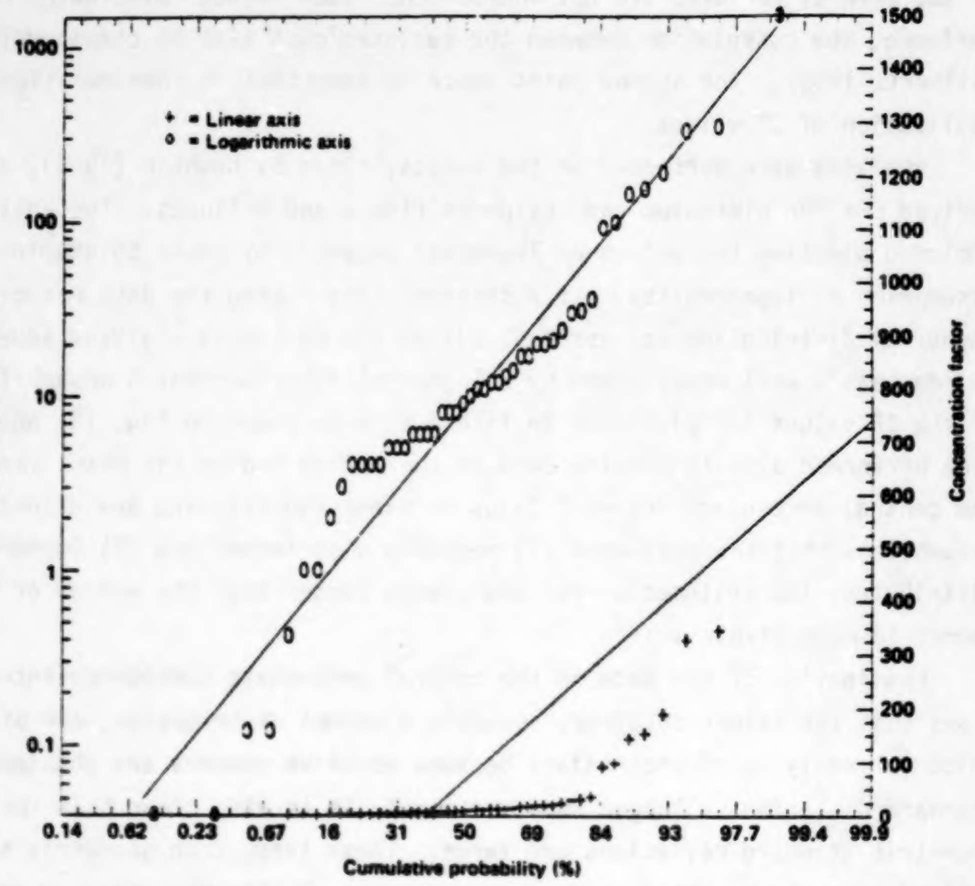

Figure 13. Concentration factors for plutonium in muscles of fish. The arithmetic mean is 77 (sigma = 220), and the geometric mean is 8.9 (sigma = 8.7).

Table 30. Values obtained from statistical analyses of CFs, assuming a normal distribution and a lognormal distribution.

Organism	Number	Median	Normal distribution			Lognormal distribution			
			Mean	S.D.[a]	Central 65% interval	GM[b]	S.D.	Central 68% interval	Central 95% interval
Plutonium									
Fish									
Muscle	48	9.5	68	220	-152 to 288	9.5	7.8	1.2 to 74	0.2 to 530
Bone	22	77	160	180	-20 to 340	64	5.4	12 to 350	2.4 to 1,700
Liver	17	64	1400	2400	-1000 to 3800	130	14	9.3 to 1800	0.7 to 23,000
Pelecypods									
Soft tissues	16	420	650	870	-220 to 1600	340	3.0	110 to 1000	40 to 2000
Cesium									
Fish									
Muscle	35	47	54	31	23 to 85	45	2.0	22 to 90	12 to 180
Pelecypods									
Soft tissues	10	41	380	680	-300 to 1100	74	7.6	10 to 560	1.4 to 3900

[a] S.D., standard deviation.
[b] GM, geometric mean.

- Critically review the data for systematic or other biases to derive the most appropriate values for the particular application.

Single values of CFs for plutonium and cesium in fish muscle and soft tissues of molluscs to be used in models have been selected previously by others (Table 31). Comparison of those values to the means given in this report, which were calculated from the data base from Noshkin (1985), shows that most are within reasonable agreement, considering the variance of the data. However, the range of values given differ considerably from the confidence intervals calculated.

Elimination Rates

It is important in determining the elimination of radionuclides that (1) the initial pulse labeling of the organisms be performed over a length of time sufficient to label long-lived compartments and (2) the loss be followed long enough to identify long-lived compartments. If data on long-lived compartments are not available, then wrong conclusions can be drawn about the retention of radionuclides and their potential for transfer to man. For example, recent seasonal data from Mussel Watch program (Goldberg *et al*., 1978) showed that 50% of the plutonium and americium were eliminated within 3 to 10 weeks. The predictions that might be made as to when contaminated mussels might be safe to ingest after a period of depuration would be considerably longer if the Guary and Fowler (1981) data were used than if the Goldberg *et al*. (1978) data were used.

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Table 31. CF values for use in models to predict the dose to man or aquatic organisms from the release of radionuclides into marine environments.

Organism	Thompson *et* *al*. (1972)	IAEA (1985)	This report Mean	This report GM
		Plutonium		
Fish				
Muscle	3.5	40 (0.5 to 100)[a]	68	9.5
Molluscs				
Soft tissues	100[b]	3000 (500 to 5000)[c]	650[d]	340[d]
		Cesium		
Fish				
Muscle	30	100 (10 to 300)	54	45
Molluscs				
Soft tissues	20[b]	30 (10 to 50)[c]	380[d]	74[d]

[a] Numbers in parenthesis are ranges.

[b] Invertebrates.

[c] Molluscs except cephalopods.

[d] Pelecypods.

REFERENCES

J.C. Amiard, A Study of the Uptake and Toxicity of Some Stable and Radioactive Pollutants in Marine Organisms: Antimony, Silver, Cobalt and Strontium in Molluscs, Crustaceans and Teleosts, Ph.D. dissertation, Centre d'Etudes Nucleaires de Fontenay-aux-Roses, Paris, France (1978).

J.C. Amiard and C. Amiard-Triquet, "Health and Ecological Aspects of Cobalt-60 Transfer in a Seawater Food Chain Typical of an Intertidal Mud Flat," International Journal of Environmental Studies 10, 113-118 (1977).

C. Amiard-Triquet, "Etude Comparative de la Contamination par le Cobalt 60 et le Cesium 137 de Quelques Invertebres Marins Fouisseurs," Vie Milieu Serie A 25, 19-40 (1975).

C. Amiard-Triquet and J.C. Amiard, "L'Organotropisme du Co-60 chez Scrobicularia plana et Carcinus maenas en Fonction du Vecteur de Contamination," Oikos 27, 122-126 (1976a).

C. Amiard-Triquet and J.C. Amiard, "Influence du Mode de Contamination sur l'Elimination du Cobalt-60 par Scrobicularia plana (Mollusque bivalve) et Carcinus maenas (Crustacea decapode)," Cahiers de Biologie Marine 17, 1-8 (1976b).

J. Ancellin and A. Vilquin, "Nouvelles Etudes de Contaminations Experimentales d'Especes Marines par le Cesium-137, le Ruthenium-106 et le Cerium-144, Radioprotection 3, 185-213 (1968).

L.S. Argiero, S. Manfredini, and G. Palmas, "Absorption de Produits de Fission par des Organismes Marins," Health Physics 12, 1259-1265 (1966).

S.R. Aston and S.W. Fowler, "Experimental Studies on the Bioaccumulation of Plutonium from Sea Water and a Deep-Sea Sediment by Clams and Polychaetes," Journal of Environmental Radioactivity 1, 67-78 (1984).

M. Avargues, J. Ancellin, and A. Vilquin, "Recherces Experimentales sur l'Accumulation des Radionucleides par les Organismes Marins," Revue Internationale Oceanographie Medicale 11, 87-100 (1968).

J.P. Baptist, D.E. Hoss, and C.W. Lewis, "Retention of Cr-51, Fe-59, Co-60, Zn-65, Sr-85, Nb-95, In-141m, and I-131 by the Atlantic Croaker (*Micropogon undulatus*)," *Health Physics* *18*, 141-148 (1970).

J.P. Baptist and T.J. Price, "Accumulation and Retention of Cesium-137 by Marine Fishes," *Fisheries Bulletin* *206*, 177-187 (1962).

T.M. Beasley and F.A. Cross, "A Review of Biokinetic and Biological Transport of Transuranic Radionuclides in the Marine Environment," *Transuranic Elements in The Environment*, W.C. Hanson, Ed. (Technical Information Center/U.S. Department of Energy, Washington, DC, DOE/TIC-22800, 1980), pp. 524-540.

T.M. Beasley and S.W. Fowler, "Plutonium and Americium: Uptake from Contaminated Sediments by the Polychaete *Nereis* *diversicolor*," *Marine Biology* *38*, 95-100 (1976).

S. Bonotto, A. Bossus, G. Nuyts, R. Kirchmann, G. Cantillon, and R. Declerck, "Contamination d'Organismes Marins par le ^{3}H, le ^{134}Cs et le ^{60}Co," *Revue Internationale Oceanographie Medicale* *49*, 127-133 (1978).

S. Bonotto, G. Carraro, S. Stract, A. Luttke, J. Colard, G. Koch, and R. Kirchmann, "Ten Years of Investigation on Radioactive Contamination of the Marine Environment," *Impacts of Radionuclide Releases into the Marine Environment* (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 649-660.

H. Boroughs, S. J. Townsley, and R. W. Hiatt, "The Metabolism of Radionuclides by Marine Organisms. I. The Uptake, Accumulation and Loss of Strontium-89 by Fishes," *Biological* *Bulletin* *111*, 336-351 (1956).

H. Boroughs, W.A. Chipman, and T.R. Rice, "Laboratory Experiments on the Uptake, Accumulation and Loss of Radionuclides by Marine Organisms," *The Effects of Atomic Radiation on Oceanography and Fisheries* (National Academy of Science - National Research Council, Washington, D.C., Publ. No. 551, 1957), pp. 80-87.

H. Boroughs, S.J. Townsley, and W. Ego, "The Accumulation of Y-90 from an Equilibrium Mixture of Sr-90-Y-90 by *Artemia salina* (L.)," *Limnology and Oceanography* *3*, 413-417 (1958).

G.W. Bryan, "The Accumulation of Radioactive Caesium in Crabs," *Journal of the Marine Biological Association of the United Kingdom* *41*, 551-575 (1961).

G.W. Bryan, "The Accumulation of Radioactive Caesium by Marine Invertebrates," *Journal of the Marine Biological Association of the United Kingdom* *43*, 541-565 (1963).

G.W. Bryan, "Ionic Regulation of the Squat Lobster *Galathea squamifera*, with Special Reference to the Relationship Between Potassium Metabolism and the Accumulation of Radioactive Caesium," *Journal of the Marine Biological Association of the United Kingdom* *45*, 97-113 (1965).

G.W. Bryan and E. Ward, "Potassium Metabolism and the Accumulation of 137-Caesium by Decapod Crustacea," *Journal of the Marine Biological Association of the United Kingdom* *42*, 199-241 (1962).

W.A. Chipman, "Accumulation of Radioactive Materials by Fishery Organisms," *Proceedings of the Gulf and Caribbean Fisheries Institute*, 11th Annual Session, 1956, pp. 97-110 (1959).

E.F. Corcoran and J.F. Kimball, Jr., "The Uptake, Accumulation, and Exchange of Strontium-90 by Open Sea Phytoplankton," *Radioecology*, V. Schultz and A.W. Klement, Jr., Eds. (Reinhold Publishing, NY, and American Institute of Biological Sciences, Washington, DC, 1963), pp. 187-191.

P.J. Coughtrey and M.C. Thorne, *Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems*, Vol. I (A.A. Balkema, Rotterdam, 1983a), 496 pp.

P.J. Coughtrey and M.C. Thorne, *Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems*, Vol. II (A.A. Balkema, Rotterdam, 1983b), 500 pp.

G. Cranmore and F.L. Harrison, "Loss of Cs-137 and Co-60 from the Oyster, *Crassostrea gigas*," *Health Physics* *28*, 319-333 (1975).

H. Dahlgaard, "Loss of Cr-51, Mn-54, Co-57, Fe-59, Zn-65 and Cs-134 by the Mussel *Mytilus edulis*," *Impacts of Radionuclide Releases into the Marine Environment* (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 361-370.

N.S. Fisher, B.L. Olson, and V.T. Bowen, "Plutonium Uptake by Marine Phytoplankton in Culture," *Limnology and Oceanography* *25*, 823-839 (1980).

N.S. Fisher, P. Bjerregaard, and S.W. Fowler, "Interactions of Marine Plankton with Transuranic Elements. I. Biokinetics of Neptunium, Plutonium, Americium, and Californium in Phytoplankton," *Limnology and Oceanography* *28*, 432-447 (1983a).

N.S. Fisher, P. Bjerregaard, and L. Huynh-ngoc, "Interactions of Marine Plankton with Transuranic Elements. II. Influence of Dissolved Organic Compounds on Americium and Plutonium Accumulation in a Diatom," *Marine Chemistry* *13*, 45-46 (1983b).

N.S. Fisher, K.A. Burns, R.D. Cherry, and M. Heyraud, "Accumulation and Cellular Distribution of ^{241}Am, ^{210}Po, and ^{210}Pb in Two Marine Algae," *Marine Ecology* *11*, 233-237 (1983c).

S.W. Fowler and J.C. Guary, "High Absorption Efficiency for Ingested Plutonium in Crabs," *Nature* *266*, 827-828 (1977).

S.W. Fowler and M. Heyraud, "Accumulation and Retention of Am-241 in Marine Plankton," *Activities of the International Laboratory of Marine Radioactivity* (International Atomic Energy Agency, Vienna, Austria, IAEA-163, 1974), pp. 28-32.

S.W. Fowler, M. Heyraud, and T.M. Beasley, "Experimental Studies of Plutonium Kinetics in Marine Biota," *Impacts of Nuclear Releases into the Aquatic Environment* (International Atomic Energy Agency, Vienna, Austria, 1975), pp. 157-177.

S.W. Fowler, M. Heyraud, and R.D. Cherry, "Accumulation and Retention of Plutonium by Marine Zooplankton," Activities of the International Laboratory of Marine Radioactivity (International Atomic Energy Agency, Vienna, Austria, IAEA-187, 1976), pp. 42-50.

S.W. Fowler, L.F. Small, and J.M. Dean, "Experimental Studies on Elimination of Zinc-65, Cesium-137, and Cerium-144 by Euphausiids," Marine Biology 8, 224-231 (1971).

A. Fraizier and A. Vilquin, "An Experimental Study of Cs-137 Elimination in the Mullet Mugil chelo and the Blenny Blennius pholis," Marine Biology 10, 154-156 (1971).

S.G. George and A. Viarengo, "Integration of Current Knowledge of the Uptake, Metabolism and Intracellular Control of Heavy Metals in Mussels," Pollution and Physiology of Marine Organisms, A. Calabrese, F.P. Thurberg, F.J. Vernberg, W.B. Vernberg, Eds. (1985), in press.

R.O. Gilbert, TRAN-STAT, Statistics for Environmental Transuranic Studies, No. 7, Pacific Northwest Laboratories, Richland, WA, PNL-SA-7585 (1979).

R.O. Gilbert, TRAN STAT, Statistics for Environmental Transuranic Studies, No. 25, Pacific Northwest Laboratories, Richland, WA, PNL-SA-11845 (1983).

E.D. Goldberg, V.T. Bowen, J.W. Farrington, G. Harvey, J.H. Martin, P.L. Parker, R.W. Risebrough, W. Robertson, E. Schneider, and E. Gamble, "The Mussel Watch," Environmental Conservation 5, 101-125 (1978).

M.C. Grillo, J.C. Guary, and S.W. Fowler, "Comparative Studies on Transuranium Nuclide Biokinetics in Sediment-Dwelling Invertebrates," Impacts of Radionuclide Releases into the Marine Environment (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 273-292.

J.C. Guary, Recherces sur les Transferts et la Fixation du Plutonium, de l'Americium et du Neptunium dans le Milieu Marin, Ph.D. dissertation, Universite d'Aix-Marseille, France (1980), 266 pp.

J.C. Guary and S.W. Fowler, "Americium-241 and Plutonium-237 Turnover in Mussels (*Mytilus galloprovincialis*) Living in Field Enclosures," *Estuarine, Coastal and Shelf Science* *12*, 193-203 (1981).

J.C. Guary and S.W. Fowler, "Experimental Studies on the Biokinetics of Plutonium and Americium in the Cephalopod *Octopus vulgaris*," *Marine Ecology Progress Series* *7*, 327-335 (1982).

J.C. Guary and A. Fraizier, "Influence of Trophic Level and Calcification on the Uptake of Plutonium Observed In-situ in Marine Organisms," *Health Physics* *32*, 21-28 (1977).

J.C. Guary, J.J.W. Higgo, R.D. Cherry, and M. Heyraud, "High Concentrations of Transuranics and Natural Radioactive Elements in the Branchial Hearts of the Cephalopod *Octopus vulgaris*," *Marine Ecology Progress Series* *4*, 123-126 (1981).

J.C. Guary and R. Negrel, "Plutonium and Iron Association with Metal-Binding Proteins in the Crab *Cancer pagurus* (L.)," *Journal of Experimental Marine Biology and Ecology* *42*, 87-98 (1980).

J. Gutknecht, "Uptake and Retention of Cesium-137 and Zinc-65 by Seaweeds," *Limnology and Oceanography* *10*, 58-66 (1965).

M.A. Hampson, "Uptake of Radioactivity by Aquatic Plants and Location in the Cells. I. The Effect of pH on the Sr-90 and Y-90 Uptake by the Green Alga *Ulva lactuca* and the Effect of Stable Yttrium on Y-90 Uptake," *Journal of Experimental Botany* *18*, 17-53 (1967).

F.L. Harrison, "Accumulation and Loss of Cobalt and Caesium by the Marine Clam, *Mya arenaria*, Under Laboratory and Field Conditions," *Radioactive Contamination of the Marine Environment* (International Atomic Energy Agency, Vienna, Austria, 1973), pp. 453-478.

C.T. Hess, C.W. Smith, and A.H. Price, "A Mathematical Model of the Accumulation of Radionuclides by Oysters (*Crassostrea virginica*) Aquacultured in the Effluent of a Nuclear Power Reactor to Include Major Biological Parameters," *Health Physics 33*, 121-130 (1977).

C.J. Hewett and D.J. Jefferies, "The Accumulation of Radioactive Caesium from Food by the Plaice (*Pleuronectes platessa*) and the Brown Trout (*Salmo trutta*)," *Journal of Fish Biology 13*, 143-153 (1978).

Y. Hiyama, *Studies on Uptake of Radioisotopes by Edible Marine Products*, Progress Reports Tokyo University 1960-1962, Report No. NP-15159 (1962).

Y. Hiyama and J.M. Khan, "On the Concentration Factors of Radioactive I, Co, Fe, and Ru in Marine Organisms," *Records of Oceanographic Works in Japan 7*, 43-77 (1964).

Y. Hiyama and M. Shimizu, "On the Concentration Factors of Radioactive Cs, Sr, Cd, Zn, and Ce in Marine Organisms," *Records of Oceanographic Works in Japan 7*, 79-106 (1964).

V.F. Hodge, F.L. Hoffman, and T.R. Folsom, "Rapid Accumulation of Plutonium and Polonium on Giant Brown Algae," *Health Physics 27*, 29-35 (1974).

M. Hoppenheit, C.N. Murray, and D.S. Woodhead, "Uptake and Effects of Americium-241 on a Brackish-water Amphipod," *Helgolander Meeresuntersuchungen 33*, 138-152 (1980).

International Atomic Energy Agency (IAEA), *Sediment K_ds and Concentration Factors for Radionuclides in the Marine Environment* (International Atomic Energy Agency, Vienna, Austria, 1985, in press), 79 pp.

D.W. Jackson, L.S. Gomez, and M.G. Marietta, *Compilation of Selected Marine Radioecological Data for the U.S. Subseabed Program*, Sandia Laboratory, Albuquerque, NM, SAND83-1725, Unlimited Release, UC-70 (1983).

D.F. Jefferies and C.J. Hewett, "The Accumulation and Excretion of Radioactive Caesium by the Plaice (Pleuronectes platessa) and the Thornback Ray (Raja clavata), "Journal of the Marine Biological Association of the United Kingdom 51, 411-422 (1971).

K.I. Kimura and R. Ichikawa, "Accumulation and Retention of Ingested Cobalt-60 by the Common Goby," Bulletin of the Japanese Society of Sciences and Fisheries 38, 1097-1103 (1972).

R. Kirchmann, S. Bonotto, A. Bossus, C. Nuyts, R. Declerck, and G. Cantillon, "Utilization d'une Chaine Trophique Experimentale par l'Etude du Transfert du ^{60}Co," Revue Internationale Oceanographie Medicale 48, 177-124 (1977).

T. Koyanagi, M. Nakahara, and M. Imura, "Absorption of Sediment Bound Radionuclides through the Digestive Tract of Marine Demersal Fishes," Journal of Radiation Research 19, 295-305 (1978).

J.C. Lemee, J. Ancellin, and A. Vilquin, "Contamination de Crevettes Roses (Leander seratus P.) au Moyen de Caesium-137 par Voie Alimentaire," Radioprotection 6, 133-142 (1970).

De. C. Martin, Proceedings Ninth Pacific Scientific Conference (1957), 16, 167-169 (1958).

S. Mattsson, R. Finck, and M. Nilsson, "Distribution of Activation Products from Barseback Nuclear Power Plant (Sweden) in the Marine Environment. Temporal and Spatial Variations as Established by Seaweed," Environmental Pollution (Series B) 1, 105-115 (1980).

P. Miramand, P. Germain, and H. Camus, "Uptake of Americium and Plutonium from Contaminated Sediments by Three Benthic Species: Arenicola marina, Corophium volutator and Scrobicularia plana," Marine Ecology Progress Series 7, 59-65 (1982).

P. Miramand and J.C. Guary, "Association of Americium-241 with Adenochromes in the Branchial Hearts of the Cephalopod Octopus vulgaris," Marine Ecology Progress Series 4, 127-129 (1981).

F. Morgan, "The Uptake of Radioactivity by Fish and Shellfish. I. Caesium-134 by Whole Animals," Journal of the Marine Biological Association of the United Kingdom 44, 259-271 (1964).

C.N. Murray, M. Hoppenheit, and H. Rade, "Accumulation of Americium 243 in Selected Brackish and Marine Invertebrates," Helgoländer wiss. Meeresunters 31, 34-54 (1978).

C.N. Murray and W. Renfro, "Uptake of Plutonium from Seawater and Sediment by a Marine Polychaete Worm," Journal of the Oceanographical Society of Japan 32, 249-252 (1976).

M. Nakahara, R. Ueda, Y. Suzuki, T. Ishii, and H. Suzuki," Concentrations of Radioactive Cobalt by Seaweeds in the Food Chains," Impacts of Nuclear Releases into the Marine Environment (International Atomic Energy Agency Vienna, Austria, 1975), pp. 301-312.

M. Nakahara, T. Koyanagi, and M. Saiki, "Concentration of Co-60 by Marine Organisms through Sediments," First Report on Estimation of Dose from Exposure to Natural and Manmade Radiation in the Environment, National Institute of Radiological Sciences, Chiba, Japan, NIRS-R-5, pp. 11-13 (1976).

M. Nakahara, T. Koyanagi, and M. Saiki, "Temperature Effect on the Concentration of Radionuclides by Marine Organisms," Journal of Radiation Research 18, 12-131 (1977).

M. Nakahara, T. Koyanagi, and M. Saiki, "Peculiar Accumulation of Co-60 by the Branchial Heart of Octopus," Bulletin of the Japanese Society of Scientific Fisheries 45, 539 (1979a).

M. Nakahara, S. Hirano, T. Ishii, and T. Koyanagi, "Accumulation and Excretion of Cobalt-60 Taken up from Seawater by Marine Fish," Bulletin of the Japanese Society of Scientific Fisheries 45, 1423-1428 (1979b).

M. Nakahara, T. Koyanagi, T. Ueda, and C. Shimizu, "Uptake and Accumulation of ^{60}Co by Octopus vulgaris through Different Mediums (Seawater and Food)," Journal of Radiation Research 22, 74 (1981).

D.J. Nelson, "Clams as Indicators of Sr-90," *Science* *137*, 38-39 (1962).

Y. Nishiwaki, Y. Kimura, Y. Honda, and K. Katsurayama, "Possible Formation of Organic Cobalt Complexes with Amino Acids and Uptake by Marine Bivalve," *Impacts of Radionuclide Releases into the Marine Environment* (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 401-419.

V.E. Noshkin, "Ecological Aspects of Plutonium Dissemination in Aquatic Environments," *Health Physics* *23*, 537-749 (1972).

V.E. Noshkin, *Concentrations and Concentration Factors of Several Anthropogenic and Natural Radionuclides in Marine Vertebrates and Invertebrates*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91766, EPA 520/1/84/028 (1985).

V.E. Noshkin, V.T. Bowen, K.M. Wong, and J.C. Burke, "Plutonium in North Atlantic Ocean Organisms: Ecological Relationships," in *Proceeding of the Third National Symposium on Radioecology, Oak Ridge, Tennessee*, D.J. Nelson, Ed., CONF. 710501-P2 (1971), pp. 691-688.

V.E. Noshkin and K.M. Wong, "Plutonium Mobilization from Sedimentary Sources to Solution in the Marine Environment," *Proceedings of the Third Nuclear Energy Agency (NEA) Seminar (1979), Marine Radioecology* (NEA, Paris, France, 1980), pp. 165-178.

B. Patel, S. Patel, M.C. Balani, and S. Pawar, "Flux of Certain Radionuclides in the Blood Clam *Anadara* *granosa* L. under Environmental Conditions," *Journal of Experimental Marine Biology and Ecology* *35*, 177-195 (1978).

R.J. Pentreath, "The Accumulation from Water of Zn-65, Mn-54, Co-58 and Fe-59 by the mussel *Mytilus* *edulis*," *Journal of the Marine Biological Association of the United Kingdom* *53*, 127-143 (1973a).

R.J. Pentreath, "The Accumulation from Sea Water of ^{65}Zn, ^{54}Mn, ^{58}Co, and ^{59}Fe by the Thornback Ray, *Raja* *clavata* L.," *Journal of Experimental and Marine Biology and Ecology* *12*, 327-334 (1973b).

R.J. Pentreath, "Radionuclides in Marine Fish," *Oceanography and Marine Biology - An Annual Review*, H. Barnes, Ed. (Aberdeen University Press, Aberdeen, 1977), pp. 368-460.

R.J. Pentreath, "Pu-237 Experiments with the Plaice *Pleuronectes platessa*," *Marine Biology 48*, 327-335 (1978a).

R.J. Pentreath, "Pu-237 Experiments with the Thornback Ray *Raja clavata*," *Marine Biology 48*, 337-342 (1978b).

R.J. Pentreath, "The Biological Availability to Marine Organisms of Transuranium and Other Long-Lived Nuclides," *Impacts of Radionuclide Releases into the Marine Environment* (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 241-272.

G.G. Polikarpov, "Ability of Some Black Sea Organisms to Accumulate Fission Products," *Science 133*, 1127-1128 (1961).

G.G. Polikarpov, *Data on Accumulation Coefficients of P-32, S-35, Sr-90, Y-91, Cs-137, and Ce-144 in Marine Organisms* (National Technical Information Service JPRS:24,227, Springfield, VA, 1964), 26 pp.

G.G. Polikarpov, *Radioecology of Aquatic Organisms* (Reinhold Book Division, New York, 1966), 314 pp.

T.J. Price, "Accumulation of Radionuclides and the Effects of Radiation on Molluscs," *Biological Problems in Water Pollution, 3rd Seminar, 1962* (U.S. Public Health Service 999WP-25, 1965), pp. 202-210.

M.S. Quinby-Hunt and K.K. Turekian, "Distribution of Elements in Sea Water," *EOS Transactions, American Geophysical Union 64*, 130-132 (1983).

T.R. Rice, "The Accumulation and Exchange of Strontium by Marine Planktonic Algae," *Limnology and Oceanography 1*, 123-138 (1956).

D.D. Ryndina, "Processes of Sorption and Desorption of Radionuclides by Marine Deposits, Algae and Detritus," *Marine Radioecology*, G.G. Polikarpov, Ed. (USAEC Translation Series AEC-tr-7299, Springield, VA, 1972), pp. 53-71.

R. Scott, "A Study of Caesium Accumulation by Marine Algae," *Radioisotopes Conference*, Vol. 1, J.E. Johnson, R.A. Faires, and R.J. Millet Eds. (Butterworth Scientific Publications, London, 1954), pp. 373-380.

M. Shimizu, T. Kajihara, and Y. Hiyama, "Uptake of Co-60 by Marine Animals," *Records of Oceanographic Works in Japan* *10*, 137-145 (1970).

R.B. Spies, K.V. Marsh, and J.R. Kercher, "Dynamics of Radionuclide Exchange in the Calcareous Algae *Halimeda* at Enewetak Atoll," *Limnology and Oceanography* *26*, 74-85 (1981).

G.M. Spooner, "Observations of the Absorption of Radioactive Strontium and Yttrium by Marine Algae," *Journal of the Marine Biological Association of the United Kingdom* *28*, 587-625 (1949).

Y. Suzuki, M. Nakahara, and R. Nakamura, "Accumulation of Cesium-137 by Useful Mollusca," *Bulletin of the Japanese Society of Scientific Fisheries* *44*, 325-329 (1978).

Y. Suzuki, M. Nakahara, R. Nakamura, and T. Ueda, "Roles of Food and Sea Water in the Accumulation of Radionuclides by Marine Fish," *Bulletin of the Japanese Society of Scientific Fisheries* *45*, 1409-1416 (1979).

W.L. Templeton, "Fission Products and Aquatic Organisms," *The Effects of Pollution on Living Material* (Institute of Biology, London, 1959), pp. 125-140.

S.E. Thompson, C.A. Burton, D.J. Quinn, and Y.C. Ng, *Concentration Factors of Chemical Elements in Edible Aquatic Organisms*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50564 Rev. 1 (1972).

V.V. Tolkach and V.V. Gromov, "Y-90 Absorption by Krill," *Oceanology* *16*, 1015-1019 (1976).

C. Triquet, "Etude de la Contamination d'Arenicola marina L. (Annelida Polychaete) par le Cobalt-60," Comptes Rendus hebdomadaires de l'Academie des Sciences, Paris (Serie D) 276, 645-658 (1973).

T. Ueda, R. Nakamura, and Y. Suzuki, "Uptake and Loss of Radionuclides by Neanthes diversicolor," Journal of Radiation Research 17, 41-42 (1976).

T. Ueda, R. Nakamura, and Y. Suzuki, "Comparison of Influences of Sediments and Sea Water on Accumulation of Radionuclides by Worms," Journal of Radiation Research 18, 84-92 (1977).

T. Ueda, R. Nakamura, and Y. Suzuki, "Comparison of Influences of Sediments and Sea Water on Accumulation of Radionuclides by Marine Organisms," Journal of Radiation Research 19, 93-99 (1978).

T. Ueda, Y. Suzuki, R. Nakamura, and M. Nakahara, "Effect of Different Combining Patterns of Radionuclides in Marine Organisms," Impacts of Radionuclide Releases into the Marine Environment (International Atomic Energy Agency, Vienna, Austria, 1981), pp. 371-380.

H.A. Vanderploeg, D.C. Parzyck, W.H. Wilcox, J.R. Kercher, and S.V. Kaye, Bioaccumulation Factors for Radionuclides in Freshwater Biota, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-5002 (1975).

J.H.D. Vangenechten, S.R. Aston, and S.W. Fowler, "Uptake of Americium-241 from Two Experimentally Labelled Deep-Sea Sediments by Three Benthic Species: a Bivalve Mollusc, a Polychaete, and an Isopod," Marine Ecology Progress Series 13, 219-228 (1983).

A.W. van Weers, "Uptake and Loss of Zn-65 and Co-60 by the Mussel Mytilus edulis L.," Radioactive Contamination of the Marine Environment, (International Atomic Energy Agency, Vienna, Austria, 1973), pp. 385-401.

A.W. van Weers, "Uptake of Cobalt-60 from Seawater and from Labelled Food by the Common Shrimp Crangon crangon (L.)," Impacts of Nuclear Releases into the Aquatic Environment (International Atomic Energy Agency, Vienna, Austria, 1975), pp. 349-361.

E.E. Ward, "Uptake of Plutonium by the Lobster, *Homarus vulgaris*," *Nature* *209*, 625-626 (1966).

R.L. Watters, D.N. Edgington, T.E. Hakonson, W.C. Hanson, M.H. Smith, F.W. Whicker, and R.E. Wildung, "Synthesis of the Research Literature," *Transuranic Elements in the Environment*, W.C. Hanson, Ed. (Technical Information Center/U.S. Department of Energy, Washington, DC, DOE/TIC-22800, 1980), pp. 1-44.

D.A. Wolfe and C.B. Coburn, Jr., "Influence of Salinity and Temperature on the Accumulation of Cs-137 by an Estuarine Clam under Laboratory Conditions," *Health Physics* *18*, 499-505 (1970).

K.M. Wong, V.F. Hodge, and T.R. Folsom, "Plutonium and Polonium Inside Giant Brown Algae," *Nature* *237*, 460-462 (1972).

J. Yen, "Sorption of Pu-237 by Two Species of Marine Phytoplankton," *Journal of Phycology* *17*, 346-352 (1981).

J.S. Young, *Biological Fate of Cobalt-60 Released During the Corrosion of Neutron-Activated Stainless Steel in Seawater*, Pacific Northwest Laboratory, Richland, WA, PNL-4217, UC-11 (1982).

V.S. Zlobin and O.V. Mokanu, "Mechanisms of the Accumulation of Plutonium-239 and Polonium-210 by the Brown Alga *Ascoplyllum nodosum* and Marine Phytoplankton," *Radiobiologiya* *10*, 584-589 (1970).

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